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EVALUATION OF THIN WALL SPACECRAFT WIRING

Volume II: Summary and Conclusions

BY

L.J. FRISCO
K.N. MATHES

SEPTEMBER 28, 1965

DEPARTMENT OF DEFENSE
PLASTICS TECHNICAL EVALUATION CENTER
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FINAL REPORT

EVALUATION OF THIN WALL SPACECRAFT ELECTRICAL WIRING

VOLUME II: SUMMARY AND CONCLUSIONS

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Report Prepared by:

L.J. Frisco
K.N. Mathes

Research and Development Center
General Electric Company
Schenectady 5, N.Y.

Report Prepared for:

NASA
Manned Spacecraft Center
Houston, Texas

Volume II

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EVALUATION OF THIN WALL SPACECRAFT ELECTRICAL WIRING

I. OBJECTIVE

The objective of this program is to determine the performance characteristics of various thin wall, spacecraft, electrical wiring under simulated spacecraft environments. The data will permit wire selection for manned spacecraft to be made on the basis of comparative performance. Further, recommendations will be made regarding the development of specifications for comparative evaluation and qualification testing of manned spacecraft electrical wire insulation.

II. EVALUATION PROGRAM

A. General

The evaluation program consisted of the following tests:

Electrical Tests

Insulation Resistance	-	Total sample immersed in water at 23°C
Voltage Withstand - 1600 volts for 1 min.	-	Total sample immersed in water
Insulation Resistance*	-	As a function of exposure time at 100% RH + dew in 15 psia pure oxygen at 50°C
Corona Start Voltage	-	In 5 psia pure dry oxygen at 93°C and in 15 psia O_2 at 100% RH + dew
Voltage Breakdown	-	In wet oxygen at 5 psia and 23°C, and at 150°C in vacuum, 10^{-6} torr
Voltage Flashover	-	In 5 psia pure oxygen at 23°C and 100% RH + dew.

*Note: Insulation Resistance and voltage breakdown are used as end point criteria of certain other tests.

Mechanical Tests

Outside Diameter	-	at 23C and 50% RH
Concentricity of Insulation	-	" " " " "
Conductor Dimensions	-	" " " " "
Weight per 100 ft.	-	" " " " "
Stripability	-	" " " " "

Mechanical Tests (Cont'd)

Solderability	-	Solder pot at 320°C
Color Durability	-	
Marking Legibility	-	
Compatibility with Potting Compounds		
Flexibility*	-	At 23°C and -196°C
Abrasion	-	At 23C
Blocking	-	150°C and 10^{-6} torr
Cut-through	-	23°C and 150°C
Thermal Creep ("Cold" Flow)	-	23°C and 150°C
Wicking	-	In water at 23°C

*Note: Flexibility is used as an end point criterion of certain other tests.

Physical - Chemical Tests

Thermal Aging	-	At 150°C in oxygen at 15 psia and in vacuum.
Exposure to Ultra-Violet	-	Approx. 1.4 x 10^6 ergs/cm^2/sec/ equiv. at 4000 A for 1 month At 85C in wet oxygen at 15 psia and at 150C in vacuum.
Exposure to Radiation	-	10 hrs. at 6000 rads/hr at 150°C and 10^{-6} torr and 100 rads/hr at 93C in 5 psia pure O_2
Flammability Smoke, flash and fire points	-	In wet flowing oxygen at 5 psia.
Chemical Compatibility	-	

Analytical Tests

Offgassing in Oxygen	-	TGA and Analysis of Gases
Volatility in Vacuum	-	TGA and Analysis at 10^{-7} torr

B. Test Methods

Details of the various test methods and equipment have been given in Volume I of the First Technical Report. A few late modifications in testing procedures are discussed in Volume I of the Final Report. No details will be given in this volume.

III. DESCRIPTION OF TEST SAMPLES

Wire No. 1

Extruded FEP nominal 5 mils with ML coating. #20 nickel plated copper 19/32 strands.

Wire No. 2

Extruded 5 mil TFE with 1 mil ML coating. #20 nickel plated copper 1/32 strands.

Wire No. 3

Double wrap H-film. First wrap: ½ lap HF tape (1 mil H, ½ mil FEP); second wrap: 1/3 lap FHF tape (½ mil FEP, 1 mil H, ½ mil FEP). 6 mil wall with ½ mil TFE dispersion overcoat with red pigment. #20 nickel plated copper 19/32 strands.

Wire No. 4

Single wrap H-film. ½ lap HF tape (1 mil H, ½ mil FEP) 3 mil wall. #20 nickel plated copper 19/32 strands.

Wire No. 5

Single wrap H-film. ½ lap FHF tape (½ mil FEP, 1 mil H, ½ mil FEP) 4 mil wall. #20 nickel plated copper 19/32 strands.

Wire No. 6

Double wrap H-film. First wrap: ½ lap HF tape (1 mil H, ½ mil FEP), second wrap: ½ lap FHF tape (½ mil FEP, 1 mil H, ½ mil FEP) with ½ mil FEP dispersion overcoat. #20 silver plated copper 19/32 strands.

Wire No. 7

Irradiated modified polyolefin 9.3 mils with polyvinylidene fluoride jacket. #20 tin plated copper 19/32 strands.

Wire No. 8

Irradiated modified polyolefin 9.2 mils. #20 tin plated copper 19/32 strands.

Wire No. 9

Type E TFE per MIL-W-1687D, 9.5 mils. #20 nickel plated copper 19/32 strands.

Wire No. 10

Single wrap H-film. 2/3 lap 3 layers of HF tape (1 mil H, ½ mil FEP). #20 nickel plated copper 19/32 strands.

Wire No. 11

Single wrap H-film. ½ lap 2 layers of ½ mil H-film with 2.5 mil TFE over-wrap. #20 nickel plated copper 19/32 strands.

Wire No. 12

Extruded silicone rubber SE9029 insulation, wall thickness 10 mils. #20 nickel plated copper, 19/32 strands.

Wire No. 13

Extruded silicone rubber (SE-9029) 10 mils, with polyvinylidene fluoride jacket 2 to 4 mils #20 nickel plated copper, 19/32 strands.

Wire No. 14

Silicone rubber (SE-9029) 10 mils, with over-wrap of H-film jacket (1 mil H, ½ mil FEP) ½ lap #20 nickel plated copper, 19/32 strands.

Wire No. 15

Double wrap H-film. First wrap: ½ lap HF tape (1 mil H, ½ mil FEP); second wrap: nominal 40% overlap FHF tape (½ mil FEP, 1 mil H, ½ mil FEP). #20 silver plated copper 19/32 strands.

Wire No. 16

Same as Wire No. 15 with a ½ mil TFE dispersion overcoat with red pigment.

IV. SUMMARY AND CONCLUSIONS

All of the detailed data are presented in Volume I of this report. A considerable amount of discussion, particularly regarding the interpretation of results, is also given in Volume I. The purposes of this second volume are: (a) to summarize the more important results, (b) to present conclusions regarding the relative performance of the various wire types and (c) to make recommendations concerning the various test procedures.

The organization of this discussion will follow the same order as that used in Volume I. Therefore, the detailed data in Volume I and the summary of that data in Volume II will appear in sections with identical numbers.

The reader is cautioned not to seek simple conclusions where performance is governed by many complex phenomena. There is no single wire construction that is best under all operating conditions encountered in spacecraft applications. Rather, an engineering compromise must be made on the basis of anticipated operating conditions and known performance characteristics of various thin wall hook-up wire constructions. The relative importance of each design consideration will vary from one application to another, even on the same spacecraft.

1. Insulation Resistance - Total Sample

Many of the wire samples were received in surprisingly short lengths. It would appear that some of the manufacturers could not produce longer lengths that would pass the acceptance tests. If the short lengths resulted from the removal of faults by the vendor, then it is rather surprising that so many wires failed the insulation resistance test (3×10^{10} ohms per 1000 feet). As shown below, only seven of the 16 wires passed the test after one hour of water immersion. At the end of one day only six wires passed the test, and these six continued to pass for the remainder of the three day immersion period.

Passed 1 Hour	Passed 1 Day	Passed 3 Days
3	3	3
6	6	6
7	7	7

(continued)

(Cont'd)	Passed 1 Hour	Passed 1 Day	Passed 3 Days
	8	8	8
	9	9	9
	10	-	-
	16	16	16

2. Voltage Withstand

Of the six wires that passed the insulation resistance test, only five also passed the voltage withstand test (1600 volts rms for 1 minute). These were wires 3, 6, 7, 8 and 16. In view of the fact that five samples of about 1000 feet each were able to pass both the insulation resistance and voltage withstand tests after three days of water immersion, these acceptance tests do not appear to be too severe.

3. Insulation Resistance - Cabled Specimens

Cabled specimens were aged for 15 days at 50°C in 15 psia pure oxygen. Insulation resistance was measured between a central wire and six surrounding wires that were connected in common.

Insulation resistance measurements are not always effective in detecting degradation or moisture absorption. Under dry conditions, d-c resistivity of most materials will increase during thermal aging, even though other properties might degrade. Under wet conditions, large decreases in resistivity are observed if moisture is absorbed more or less uniformly throughout the volume of the material. If there is a high resistance barrier, however, the measured value of insulation resistance will still be high because the barrier interferes with the charge transport process.

The results clearly showed the effectiveness of dispersion coatings in reducing moisture penetration in the taped constructions. Wires 4 and 5 showed the largest general decrease in insulation resistance with increasing exposure time, while Wires #3 (TFE dispersion) and #6 (FEP dispersion), showed relatively little change. The TFE over-wrap on Wire #11 also proved to be an effective barrier against moisture absorption.

The other wires showed no general effects of the 15 day exposure, although a few faults in Wire #2 caused occasional low values of insulation resistance to be recorded.

4. Corona Measurements

Corona inception voltage and extinction voltage was measured on the cabled specimens that were aged in wet oxygen and 15 psia for 15 days in the insulation resistance tests. Measurements were made in dry oxygen at 5 psia, $23^{o}C$ and in wet oxygen at 15 psia, $23^{o}C$. The average values are summarized in Table 4-1.

There is general agreement between wall thickness and corona inception voltage. This is to be expected simply on the basis of geometry. The values are high, however, for such thin wall insulation.

The lower values at 5 psia are, of course, the result of lower gas density. However, in several cases, the values at 15 psia were not as high as might be expected on the basis of the low pressure values. This is attributable to the formation of water drops in critical regions, particularly with those specimens that were adversely affected by the 15 day exposure at high humidity.

Corona is known to be an effective drying agent. It distorts water drops and sprays them off the surface. This accounts for the fact that the extinction voltage was sometimes higher than the inception voltage in wet oxygen at 15 psia.

There was very little variability of test results in the dry condition. In the wet condition, corona tends to seek out faults, as evidenced by occasional low values of inception or extinction voltage.

The corona measurements do provide data that are important from the design viewpoint, particularly at lower pressure, where the corona extinction voltages are less than 600 volts in several cases. These values would be appreciably lower if the pressure was decreased further, during depressurization of a spacecraft cabin, for instance. Corona measurements should certainly be made at conditions that may be encountered at any time that the electrical system is energized.

TABLE 4-1

AVERAGE CORONA INCEPTION VOLTAGE (C.I.V.) AND EXTINCTION VOLTAGE (C.E.V.) IN DRY OXYGEN AT 5 PSIA AND WET OXYGEN AT 15 PSIA. (VOLTS RMS)

	5 PSIA O_2 Dry		15 PSIA O_2 Wet	
Wire #	C.I.V.	C.E.V.	C.I.V.	C.E.V.
1	880	750	1180	1210
2	930	780	1090	1340
3	840	750	1230	1160
4	630	570	540	670
5	640	570	740	700
6	760	750	1130	1160
7	810	690	1710	1540
8	1070	960	1690	1020
9	1060	950	1430	1200
10	620	540	890	860
11	680	650	650	740
12	1130	890	1510	1160
13	970	950	1790	1710
14	1140	1070	1450	1390

Note: Measurements made on cabled specimens at end of 15 days'exposure to 15 psia wet oxygen at 50°C.

5. Voltage Breakdown in Air, Wet 5 PSI Oxygen and Vacuum at 150°C

Voltage breakdown tests on hook-up wire provide significant information of three types:

a. An estimate of the margin of safety in respect to the functional (operating) voltage requirements.
b. A basis of comparison for estimating the effect of ambient or service conditions.
c. Information about the character and uniformity of the wire insulation.

In order to consider point (a) above, in Figure 5-1, average and minimum values of voltage breakdown have been plotted for three conditions:

In normal air at 23°C and 50% RH.
In 5 PSI wet oxygen at 23°C.
In vacuum (10^{-6} torr) at 150°C.

The latter two conditions are characteristic of those ambients likely to be encountered in and around manned space vehicles. It is apparent at a glance that under vacuum conditions the minimum breakdown voltage for Wire #4 was 6.5 kilovolts. Allowing for additional statistical variation, including the effect of intimate contact in long cable runs, single insulation to ground, the effect of time and other parameter such as aging, 3 kv or less would certainly be a maximum allowable operation voltage. If inductive switching surges can occur, then the normal voltage input need be limited to only 1 kv or somewhat less. However, any of the wires should meet operational needs of a 600 volt system, unless discontinuities or gross defects are to be found in the insulation.

It should be recognized that only relatively small areas of insulation are in contact in the twisted pair specimen. Thus, the specimen does not assess wire uniformity in terms of holes or discontinuities which may occur along the length. The effect of such discontinuities are better evaluated by voltage withstand tests on long lengths of wire immersed in water. The twisted pair test assesses voltage capabilities and uniformity in respect to such design factors as insulation thickness, concentricities and tape overlap.

Voltage breakdown tests may be useful in determining the degree to which vacuum or oxygen atmospheres may affect voltage performance of the different types of wire. From Figure 5-1 it is apparent that the voltage breakdown of extruded Teflon, Wires #1, 2, and 9, is not greatly decreased in vacuum or the 5 PSI oxygen atmosphere. In contrast H-film taped Wires #3, 4, and 5 suffer a significant decrease in voltage breakdown under the same ambients. It would be easy to conjecture that the taped structure is more subject to corona or voltage discharge at low ambient pressure and in vacuum. However, extruded polyolefin insulated Wires #7 and 8 are just as much affected by the low pressure ambients as the taped structure. It is, of course, possible to explain the decrease for Wires #7 and 8 on the basis of possible non-homogeneity in the filled polyolefin material. Curiously, however, Wire #11 is an unbonded, taped insulation for which the voltage breakdown might be expected to decrease at low pressures. However, little if any significant change is apparent. It becomes obvious that the 5 PSI oxygen and vacuum ambients are not likely in themselves to cause operational voltage breakdown problems with any of the wires in the low voltage systems.

While not directly applicable to the kind of wires involved in this study, attention should be drawn to the fact that voltage breakdown decreases rather than increases in a hard vacuum. As recorded in Volume I of this final report, voltage breakdown in vacuum is accompanied or preceded by a blue glow discharge. It may be concluded that voltage stress in some way produced outgassing. Most likely, voltage breakdown occurred when the gas pressure at the surface reached the most unfavorable value. In test, the pumping speed was quite high, but of course not as high as that of space. Nevertheless, it is considered possible that in space similar outgassing at the dielectric surface or in confined spaces might produce a hazardous dielectric situation in applications involving reasonably high operating voltages.

Finally, voltage breakdown may be most useful in assessing, indirectly, the homogeneity and uniformity of the insulation. In order to provide a comparison between wires on a reasonably equivalent basis, the dielectric strength has been calculated - the average voltage breakdown

divided by double the average wall thickness.* The calculated results are plotted in Figure 5-2. The H-film taped Wires #3, 4, 5 and 6 are considerably superior to the others when compared in this way. An estimate of variability may be obtained by dividing the average value of voltage breakdown by the range (maximum less minimum value). Such results are plotted in Figure 5-3. It is then apparent that the H-film taped Wires #5 and 15 along with the ML coated Teflon extruded wires #1 and #2 and the TFE Teflon extruded Wire #9 are most variable. Wires #3, 4, 8 and 12 are the least variable. Once again Wire #3 demonstrates superior characteristics.

Voltage breakdown tests in normal air provide useful information about the character and uniformity of the wire insulation. Voltage breakdown tests in vacuum and in 5 PSI oxygen do not provide functionally useful information and the value of such results, while interesting, probably does not justify the rather considerable experimental difficulty and expense involved.

*Complete results for all the wires may be found in Volume I.

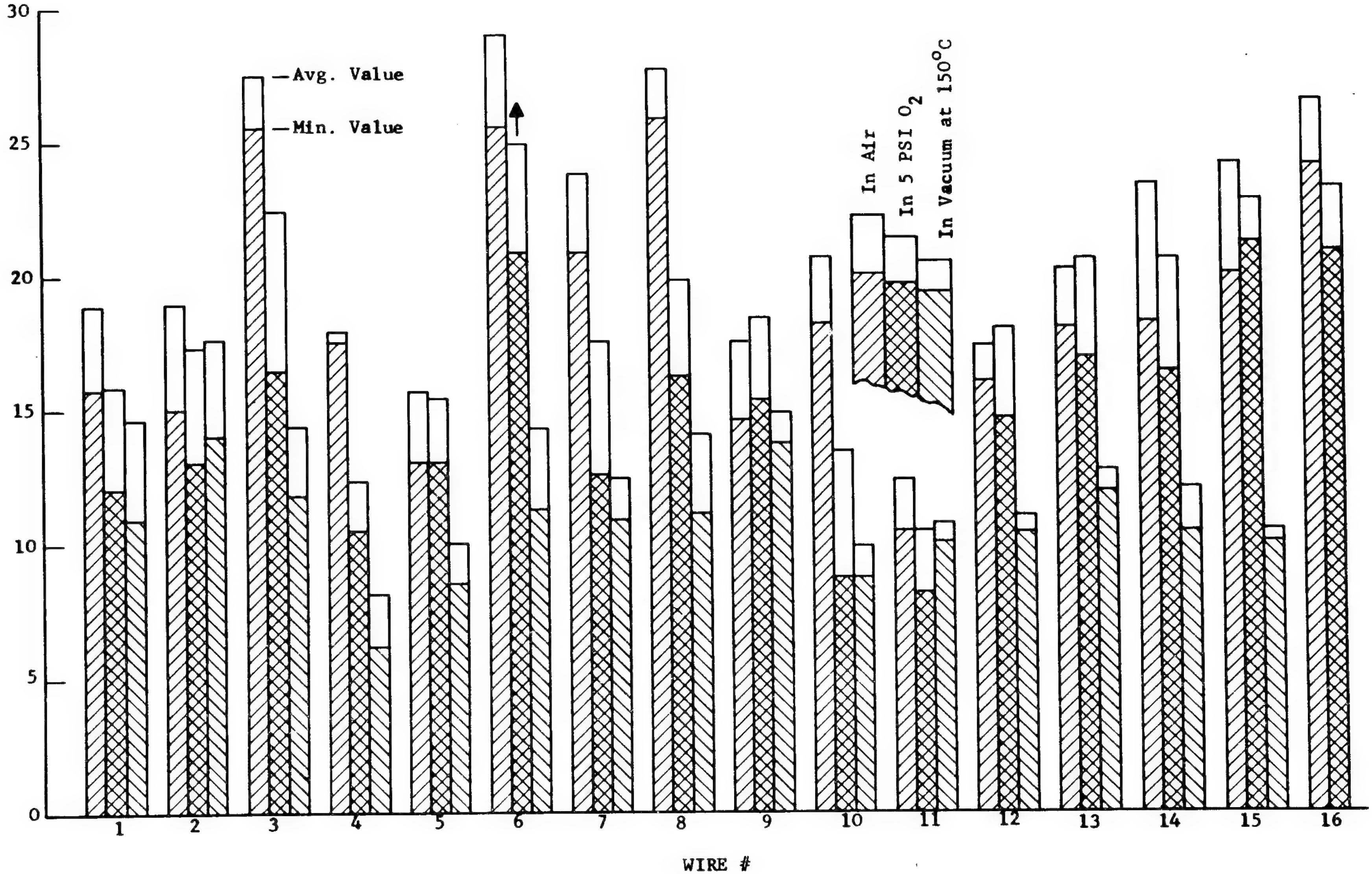

Figure 5-1 - Voltage Breakdown (Fast Rate of Rise) in Air, 5 PSI Wet Oxygen and 10^{-6} Torr Vacuum at 150°C

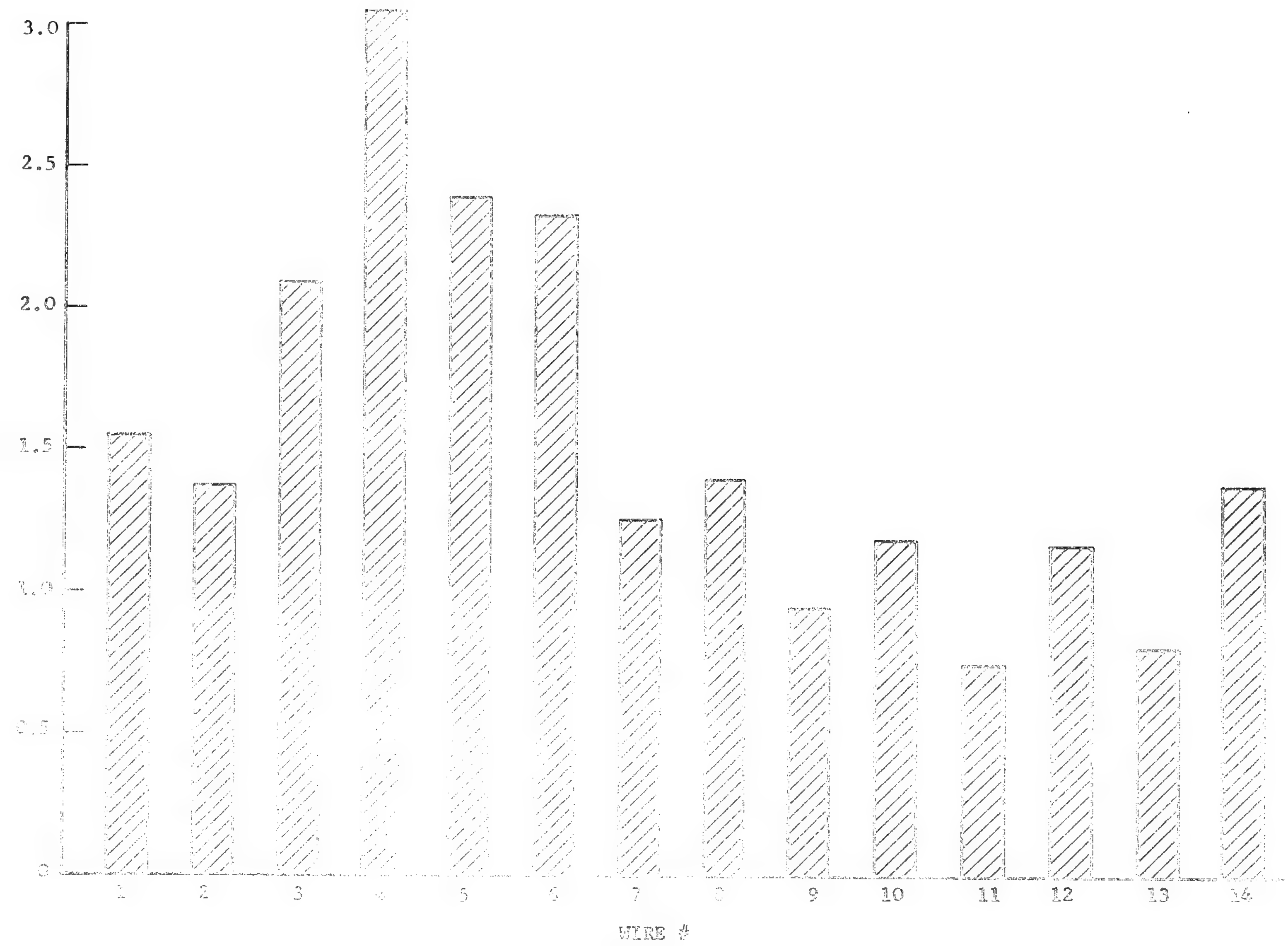

Figure 1-2 - Average Dielectric Strength (Calculated) in Air

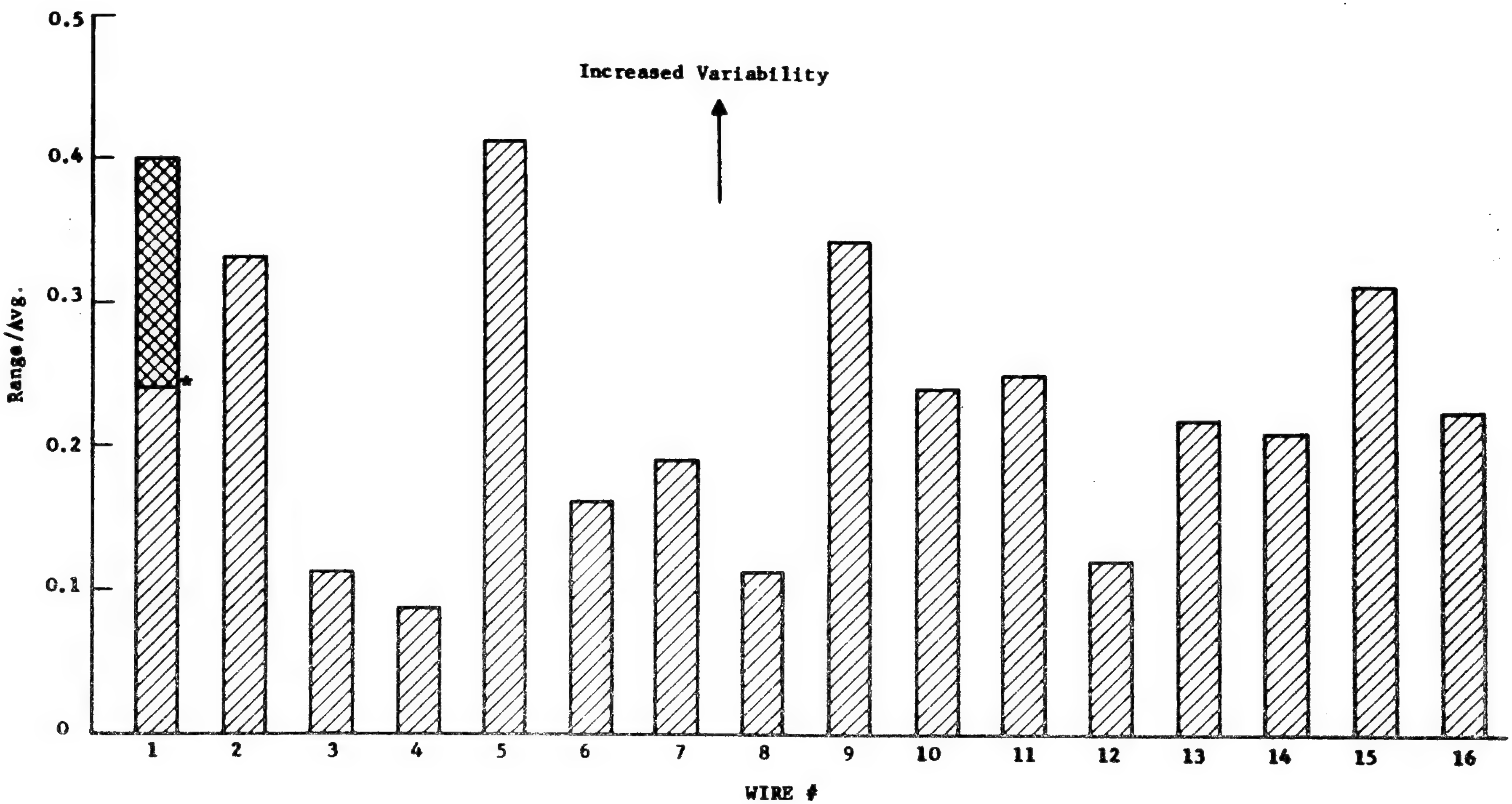

Figure 5-3 - Variability of Voltage Breakdown in Air

*Two sets of values were available.

6. Voltage Flashover

Voltage flashover may be important in spacecraft application where creepage distances over wires exist between live terminals and ground or in those chance situations where a fault exists or develops in the wire coating so that flashover can occur over the wire insulation surface to ground.

While spacecraft voltages are usually low, quite high overvoltages can occur particularly when inductive DC circuits are interrupted. In this program a 3/16" surface path failed twice at 780 volts and many failures occurred with a range of 1260 to 1680 volts. It is obviously important to recognize the possibility of flashover and guard against it by the use of potting compounds and as long as possible creepage distances at terminations which cannot be potted. The importance of freedom from faults in the wire coatings is obvious.

Even if flashover occurs it may not cause permanent damage unless tracking or fire result. Of the wire insulations in this program only wires #2 and 9 were completely free of such problems. All of the other wires burned or tracked. The polyolefin wire #8 (see Figure 6-1) and the Kynar jacketed silicone rubber #13 burned in a spectacular fashion.

When complete tracking occurs on the surface of wire insulation, even a low voltage cannot be reapplied. However, several of the H-film taped wires did not track after the first flashover. The FEP layer on the H-film and the Teflon coating on the wire surface appear to be beneficial even though not completely protective.

It should be recognized that flashover will not occur in a properly designed electrical system which is properly protected with potting compounds and free from faults. If flashover occurs in vacuum, fire will not result and the possibility of tracking is believed to be much reduced. The potential danger exists primarily in oxygen atmospheres although to a lesser extent tracking and fire may also result from flashover in normal air. Obviously inflammable contaminants, such as oil and fuel on the wire surfaces increase the likelihood of fire during a flashover. Flashover studies of contaminated surfaces have not been made but the voltage breakdown tests in the compatibility studies demonstrate the potential hazard.

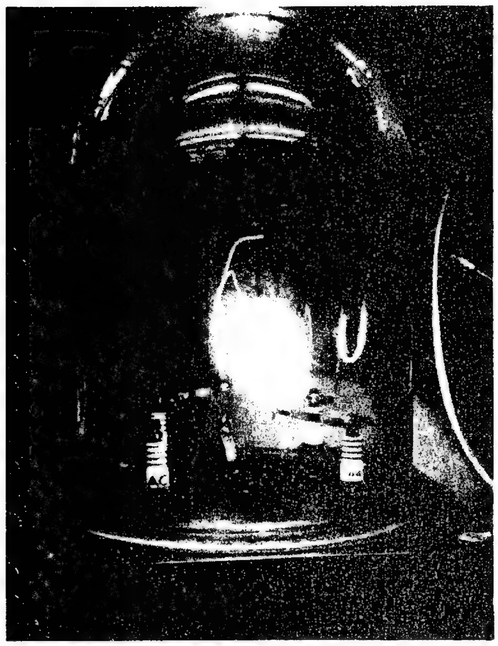

Figure 6-1: Flashover Ignites Polyolefin Wire #7 in 5 PSI Oxygen
(Note: Similar Burned Wire at Left Rear)

7. Outside Diameter

Measurements of outside diameter were made by hand micrometer, X-ray examination, optical comparator and cross-section examination. The hand micrometer and X-ray techniques are not satisfactory. The optical comparator is useful in determining maximum and minimum values. The most accurate and most useful procedure is cross-section examination. This procedure consists of microscopic examination of a specimen that is potted, cross-sectioned and polished.

With all of the wires, the difference between maximum and minimum diameter was less than 10% of either value. The differences are the cumulative result of corresponding variation in conductor diameter, wall thickness and distortion.

8. Concentricity

Concentricity measurements were made using X-ray examination and cross-section examination. Again, the cross-section provides the more accurate and useful information.

Most of the wires had average values of concentricity that were well above the 80% acceptance criterion. Wires 4, 10 and 11 missed by less than 2%, which was probably greater than the experimental error with the X-ray technique.

The 80% concentricity level does not appear to be difficult to achieve. It is recommended that measurements of concentricity be made on cross-sectioned specimens.

9. Conductor Dimensions

Conductor diameter can be determined with X-ray techniques because the coefficient of absorption is so high for copper (in contrast to the organic insulation). Again, however, the cross-section specimen provides a convenient and precise means of measuring dimensions. This is particularly true with a stranded conductor that may have individual strands that have been dislocated during the wire manufacturing process.

For this reason the cross-section measurements are somewhat higher than the X-ray measurements. On the basis of more conservative X-ray measurements, all of the wires had average values of diameter less than or equal to the allowable maximum of .041 inches.

Consideration should be given to undersized diameter also. When the average diameter is significantly below specification, the current carrying capacity of the wire is reduced according to the square of the diameter. Furthermore, isolated areas of undersized conductors are obviously undesirable. Specifications should state the minimum as well as maximum allowable diameter.

10. Weight per 1000 Feet

The average values of weight per 1000 feet are given in Table 10-1. Several wires are heavier than the suggested maximum of 4.72 pounds per 1000 feet. The weight differences are primarily, but not entirely, associated with the insulation rather than the conductor. In the case of Wires #1 and 2, which sould be approximately the same weight, Wire #2 was significantly lighter. A check on conductor weight per unit length revealed that the conductor of Wire #1 was about 0.29 pounds per 1000 foot lighter than that of Wire #2. If the conductor of Wire #1 was as heavy as the other nickel plated conductors, this wire would not pass the 4.72 pound/1000 feet criterion.

Again, it appears that minimum, as well as maximum values should be specified for a particular wire construction.

TABLE 10-1

AVERAGE WEIGHT PER 1000 FEET (POUNDS)

Wire No.	Pounds
1	4.50
2	4.86
3	4.80
4	4.22
5	4.36
6	4.45
7	4.65
8	4.65
9	5.43
10	4.21
11	4.21
12	4.95
13	5.36
14	5.41
15	4.33
16	4.46

11. Stripability

All wires except #4 and #1 could be stripped with a mechanical stripper. Some conductor damage was noted in the detailed observations reported in Volume I. With these thin walls, however, the conventional holding grip seriously damages the insulation. Mechanical grippers should not be used unless the insulation is protected from such damage by modifying the grippers.

Thermal strippers can be used with all of the wires. In the case of the H-film insulation, there was some charring evident, and the conductor was scraped.

12. Solderability

All wires except 15 and 16 were examined for solderability. Zinc chloride flux was used with the nickel plated conductors. All conductors could be easily soldered, wetting the entire surface. No insulation damage as the result of heating was observed.

13. Color Durability

Color changes were recorded in the course of conducting the various aging and compatibility tests. The polyolefin wires (#7 and 8) exhibited darkening at elevated temperature (150°C) in both vacuum and oxygen, with and without ultraviolet radiation present. In oxygen, the effect was worse, and both wires turned black. After 15 days in hydraulic oil, Wire #8 had a pink tint (the oil was red). After 20 hours in N_2O_4, Wire #8 had a greenish tint. The same exposure caused fading of the red dispersion coating of Wire #3.

With Wire #13, the Kynar jacket turned brown after 20 hours exposure to UDMH.

Wire #12 turned from black to reddish brown after 20 hours exposure to MMH.

Hydrazine and A-50 caused silicone rubber (Wires 12 and 13) to turn from black to brown with purple spots.

MMH, hydrazine and A-50 caused color changes wherever they attacked H-film, but the decomposition of the film is a much more serious problem than the color change. The discoloration does, however, permit rapid detection of decomposition under the FEP layer or dispersion coat.

Both ethyl alcohol and 5% NaCl solution caused blue-white blotches to develop under the jacket of Wire #13.

It must be concluded that color durability is not a problem in the absence of chemical attack, except for Wires #7 and 8 at high temperature. It should be noted that Wire #11 was black, and the silicone rubber on Wires #12, 13 and 14 was also black.

14. Marking Legibility

Specimens for marking legibility tests were marked by Kingsley Machine Company, Hollywood, California. The markings were made with heated type pressing a marking foil onto the surface of the wire insulation. Wires #1, 15 and 16 were not examined. Wires 4 and 5 were not aged after marking. In these cases, specimens were not available in time to be fully evaluated.

Measurements of insulation resistance and voltage withstand on water immersed specimens showed that the marking process had not degraded the electrical integrity of the insulaton on most of the wires. Only wires 4, 10, 11 and 12 were damaged. Wire #4 has the thinnest wall, so it is not surprising that it was damaged. Similarly, Wire #10 is also a single wrap construction with no overcoat. Wire #11 has a TFE overwrap which has proven to be easily damaged in other tests. Wire #12 has a thin silicone rubber insulation, which has poor mechanical strength.

The marking films and the process parameters used are summarized in Volume I, as are detailed results of the tests on marked specimens. Aging had no effect on the markings, except in wet oxygen with ultraviolet radiation. In this case the markings on Wires 2 and 10 were removed and the blue marking on Wire #7 was badly faded.

In the chemical compatibility tests, drastic effects were observed in some cases with the fuels and oxidizers. However, most of these effects were caused by degradation of ML or H-film in the presence of N_2H_4, MMH and A-50.

It must be concluded that permanent, letter marking of thin-wall hook-up wire is both feasible and practical. Further improvements in marking techniques will undoubtedly continue as experience with thin wall construction is gained.

15. Compatibility with Potting Compounds

Potting compounds should be designed to provide mechanical protection and prevent ingress of moisute and contaminants. It may be necessary for operational requirements to select a particular potting compound. It is then necessary to select components such as hook-up wire which are compatible with the potting compound. More usually the potting compound should be selected so as to be compatible with the hook-up wire.

The performance of four potting materials is compared in Figures 15-1 to 15-5 for each of four typical wires - #2, 6, 7 and 9 - which are of the greatest interest in this program. Similar plots could be made for any of the wires from the complete data in Volume I. Based on the balanced results from Figures 15-1 to 15-5, the most acceptable potting compound of the four evaluated is shown for each of the four wires in the following list:

Wire #	Most Acceptable Potting Compound
2	Epoxy XR 5038
6	Epoxy XR 5038
7	Epoxy XR 5038 (RTV Silicone #1943 is a close second)
9	Silicone #1663

An overall summary for all the wires is given in Table 15-1. In this table the minimum value obtained, whether nicked or unnicked, has been plotted. By using this table it is possible to select the best potting compound for each type of test.

As described in more detail in Volume I, positive correlation does not generally exist between values of pull-out force, voltage breakdown and insulation resistance. While nicked wires usually have poorer electrical values, this is not always so.

The rather large amount of degradation in the electrical properties for so many of the wires is rather disturbing. It is possible that the thermal aging in oxygen is at least partly responsible for the rather general degradation. The polyurethane #794 was visibly badly damaged.

It is unfortunate that time is unavailable to evaluate unaged specimens. Even so, the 14 days aging at 150°C in O_2 is considered realistic in terms of spacecraft requirements. It seems desirable to look for or develop better potting compounds than those included in this program.

TABLE 15-1

OVERALL SUMMARY - EFFECT OF POTTING COMPOUNDS ON WIRE

Wire #	Minimum Pull-Out Force-lbs.				Minimum Value Voltage Breakdown Kilovolts				Minimum Value Insulation Resistance Ohms			
	A	B	C	D	A	B	C	D	A	B	C	C
1	11.2	9.9	14.2	9.4	<0.5	0.4	<0.5	0.5	$1.0x10^7$	$1.7x10^7$	$3.3x10^6$	$3.3x10^5$
2	8.8	8.5	10.1	8.1	3.1	11.6	12.6	1.5	$3.9x10^8$	$8.3x10^9$	$3.9x10^7$	$1.0x10^6$
3	20.4	12.6	33.8	6.0	<0.5	20.0	10.0	3.5	$5.0x10^5$	$1.6x10^{12}$	$6.8x10^{12}$	$2.0x10^5$
4	15.3	12.7	28.6	10.2	3.0	9.0	7.5	1.6	$4.2x10^7$	$7.6x10^{11}$	$2.3x10^7$	$1.0x10^5$
5	15.5	11.7	14.9	7.0	<0.5	6.0	4.5	<1.0	$1.3x10^6$	$3.5x10^{11}$	$4.5x10^6$	$1.0x10^5$
6	18.6	12.3	26.5	4.9	12.5	12.5	16.8	4.0	$1.5x10^{13}$	$1.6x10^{12}$	$2.1x10^{13}$	$2.0x10^5$
7	18.3	9.5	24.7	10.2	13.0	7.0	15.7	3.9	$2.5x10^{12}$	$1.0x10^{12}$	$6.8x10^{12}$	$1.0x10^5$
8	19.2	2.6	22.2	12.4	7.5	9.0	15.5	11.6	$8.3x10^{12}$	$1.5x10^{12}$	$2.1x10^{13}$	$2.0x10^5$
9	12.0	7.7	9.6	11.0	9.5	17.6	8.0	1.5	$4.2x10^8$	$1.1x10^{12}$	short	$2.0x10^5$
10	6.7	8.8	10.7	5.4	<0.5	0.5	7.5	0	$6.6x10^6$	$5.0x10^6$	$5.0x10^{12}$	$5.6x10^5$
11	4.0	3.5	3.2	3.9	<0.5	0.2	3.0	0	$2.9x10^8$	$6.3x10^8$	$1.3x10^{13}$	$7.1x10^5$
12	14.0	11.7	11.2	1.4	11.1	8.5	4.2	1.0	$1.8x10^{15}$	$2.5x10^7$	$5.0x10^5$	$4.2x10^6$
13	6.9	4.7	0.40	7.6	8.3	4.9	3.1	11.2	$1.3x10^{12}$	$3.9x10^{11}$	$5.0x10^{12}$	$1.0x10^7$
14	9.5	10.4	7.4	4.6	11.1	7.1	10.3	4.0	$2.0x10^9$	$9.1x10^6$	$1.7x10^{13}$	$4.5x10^5$

A - RTV Silicone #1933
B - Silicone #1663
C - Epoxy XR 5038
D - Polyurethane #794

All potted specimens aged 14 days at 150^oC in Oxygen.
Electrical specimens also immersed 3 days in water.

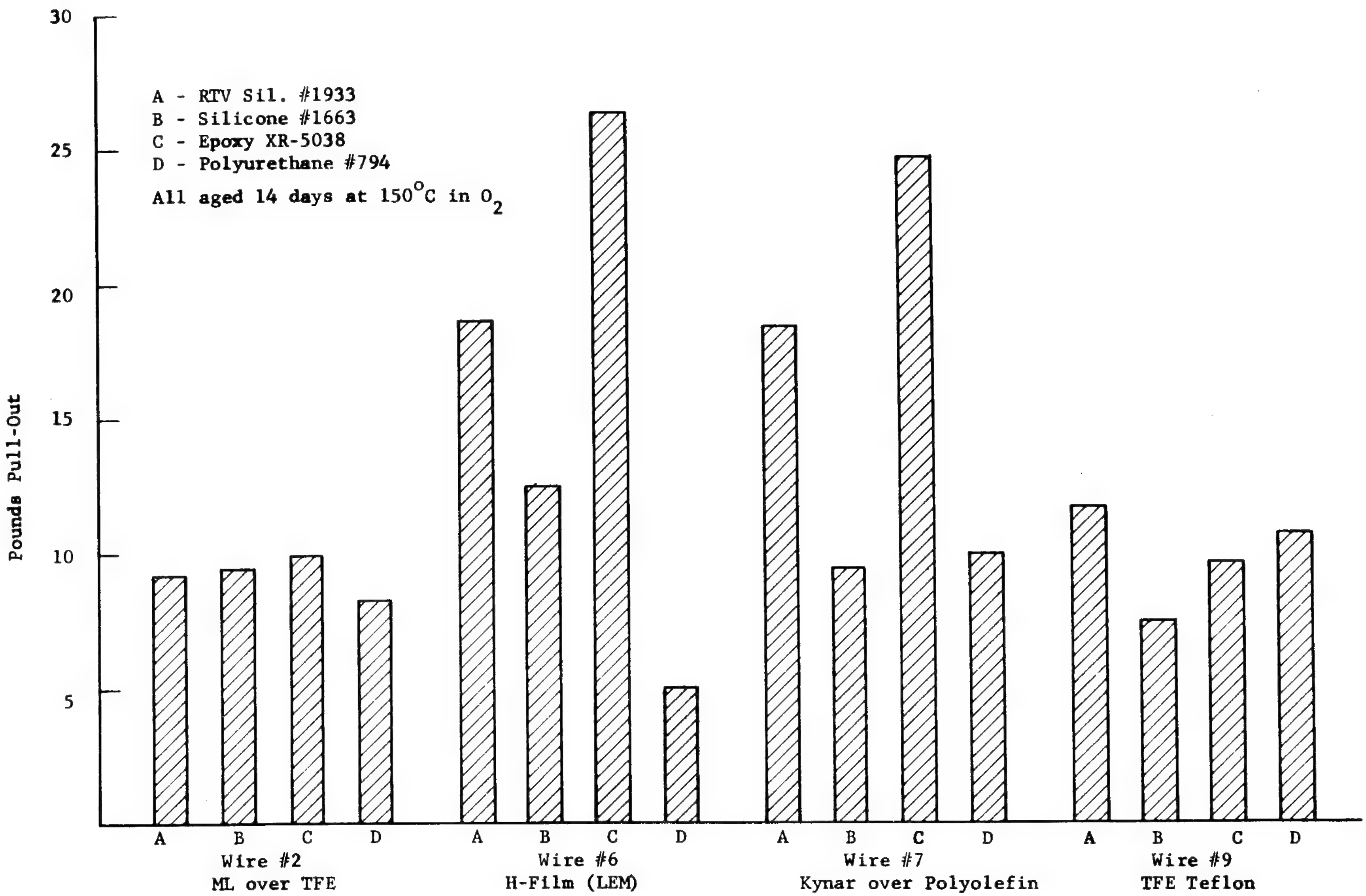

Figure 15-1 - Comparison of Minimum Pull-OUt for 4 Typical Wires in 4 Potting Compounds

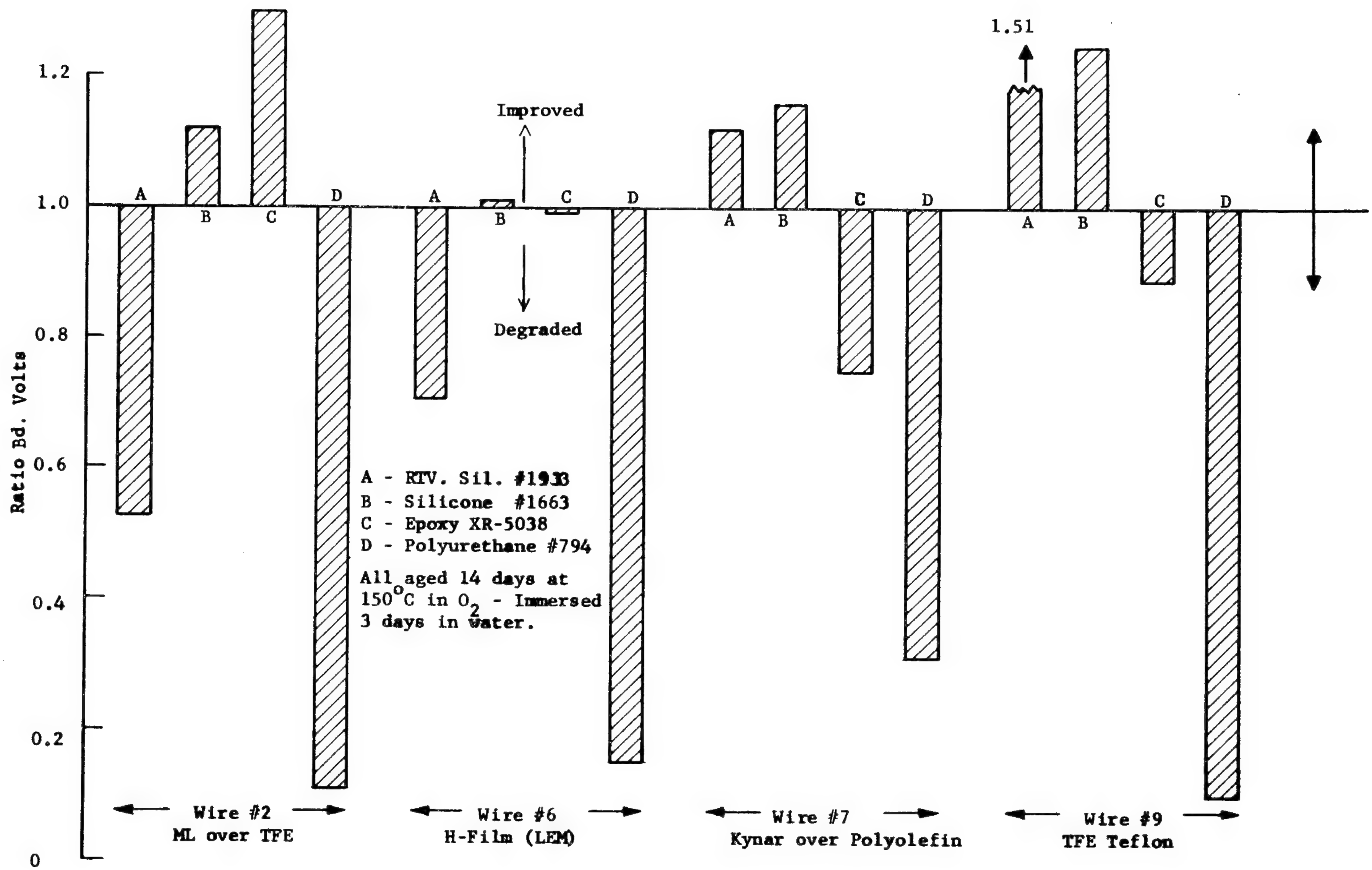

Figure 15-2 - Comparison-Ratio Breakdown Voltage - Potted/Unpotted 4 Typical Unnicked Wires in 4 Potting Compounds

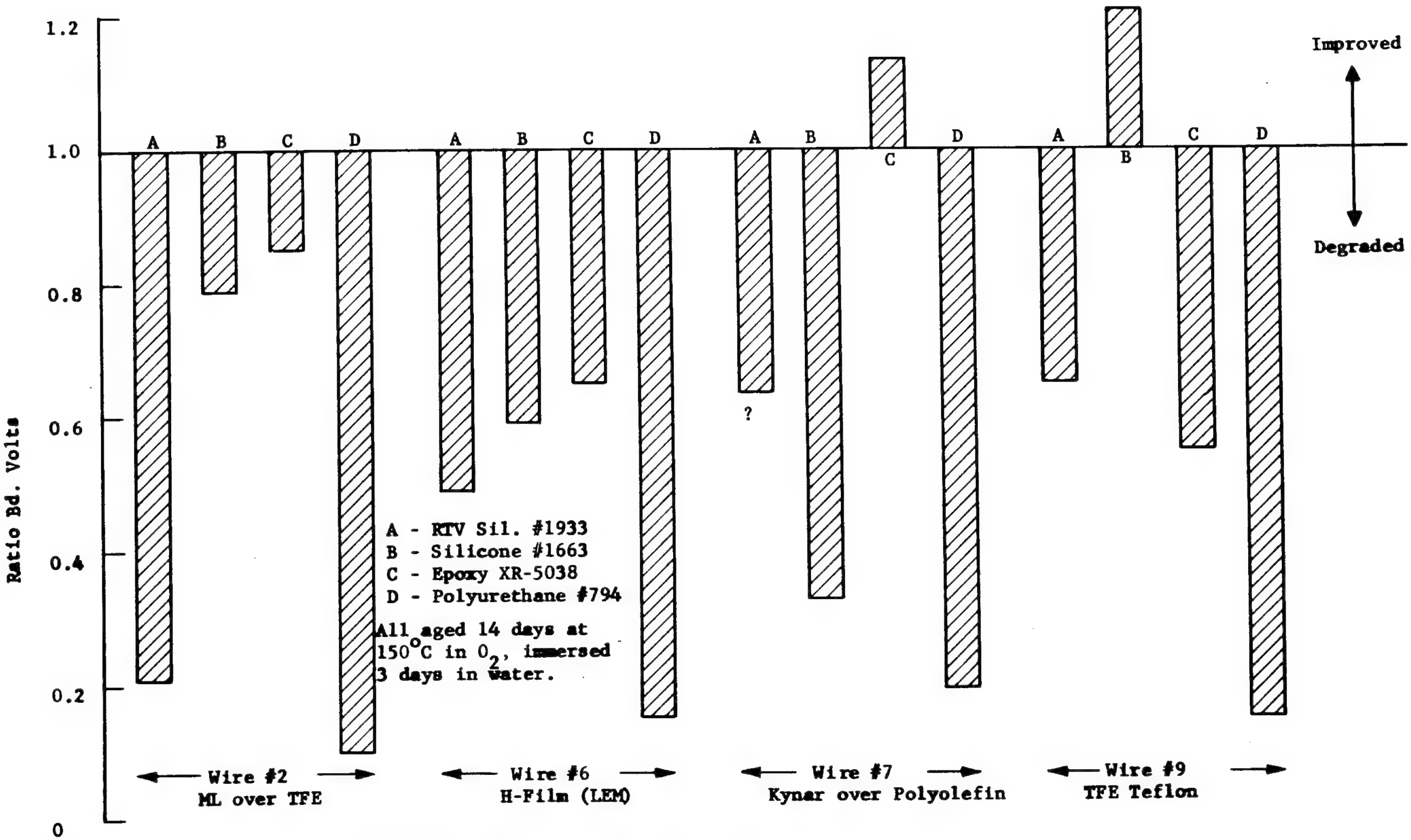

Figure 15-3 - Comparison-Ratio Breakdown Voltage - Potted/Unpotted
4 Typical Nicked Wires in 4 Potting Compounds

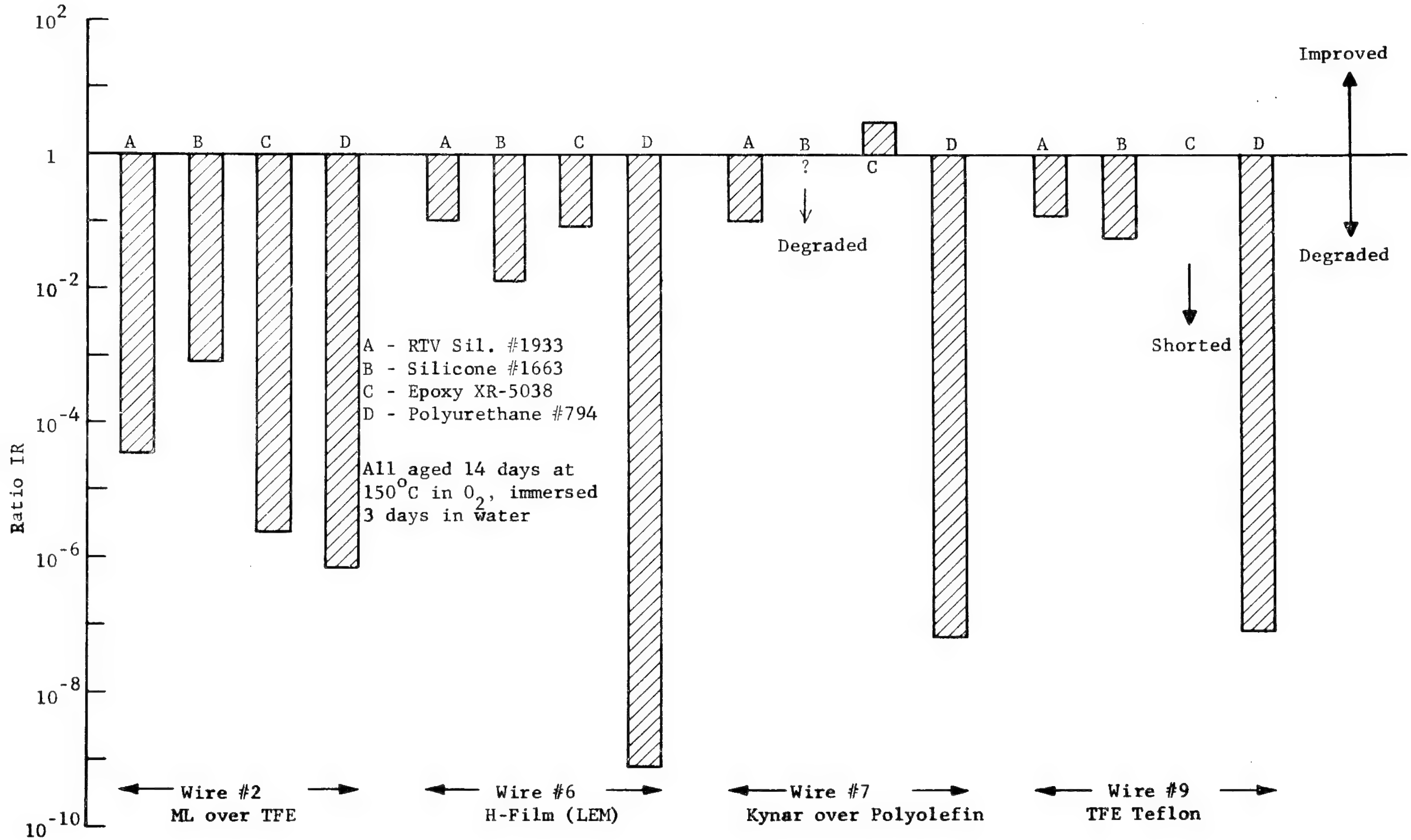

Figure 15-5 - Comparison-Ratio Insulation Resistance - Potted/Unpotted 4 Typical Nicked Wires in 4 Potting Compounds

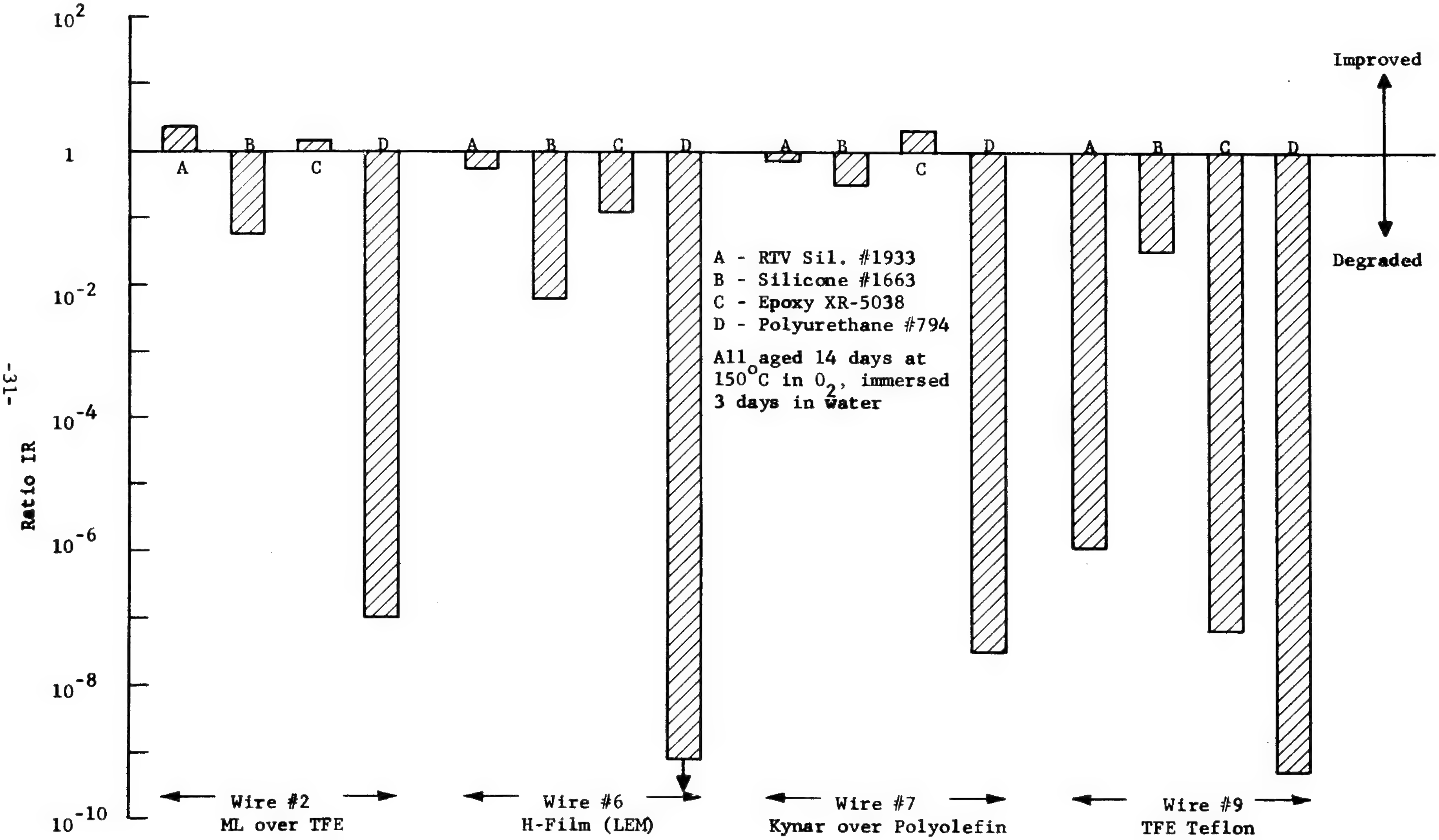

Figure 15-4 - Comparison-Ratio Insulation Resistance - Potted/Unpotted 4 Typical Unnicked Wires in 4 Potting Compounds

16. Flexibility

Mechanical failures of hook-up wires in service are often dependent upon many factors. The contribution of flexure to such failures is difficult to analyze. When the wire flexes (or ships) its surface may abrade in contact with sharp metal edges in contact with other components. From this point of view a "stiff" wire may perform best. On the other hand the wire may need to flex in service and in this case flexibility is desired. In some situations a wire under varying degrees of tension may vibrate and the conductor itself may break at the point where the wire is clamped. In such cases the interaction between the insulation and the conductor may be involved particularly if the insulation is stiff and brittle (i.e. at low temperatures or after aging).

The mandrel flexibility test provides a simple and inexpensive way of comparing flexibility particularly at low temperatures as shown in Figure 16-1. It is immediately apparent the ML overcoated Teflon Wires #1 and 2, the polyolefin Wires #7 and 8 and the silicone rubber Wires #12, 13 and 14 are brittle at -196^{o}C. It is recognized that at intermediate temperatures the rating order might be different. However, even at -196^{o}C all of the H-film taped wires (#3, 4, 5, 6, 10, 11, 15 and 16) can be bent over relatively small mandrels without failure. The performance of TFE Teflon (Wire #9) is quite good also.

At room temperature all of the wires can be wrapped around their own diameter without catastrophic failure, although the covering of overcoated wires may in some instances loosen, wrinkle or sometimes craze. It is possible that more information and comparative tests could be made at room temperature if the wires were first stretched. Of course, the amount of stretch is another variable which would need to be investigated.

Wire stiffness (rigidity) has not been measured in this program but can be important when pulling or laying wires in place or in those applications when the wire must flex in operation. Qualitatively it can be reported that all of the H-film taped wires (#3, 4, 5, 6, 10, 11, 15 and 16) are relatively stiff. The stiffness appears to depend not only on the thickness and number of tapes but also the amount of tape overlap and the angle of lay. The Teflon insulated Wires #1, 2 and 9 as well as the polyolefin Wire #8 are less stiff than the H-film taped wires but the silicone rubber (Wire #12) is the least stiff of all. However overcoats and jackets increase the stiffness of the polyolefin (Wire #7) and the silicone rubber (Wires #1,13 and 14).

The results for wires subjected to repeated flexure are summarized in Figure 16-2. Wires #6, 15 and 16 are silver plated and Wires #7 and 8 are tin plated. The remaining wires are nickel plated. Except for Wire #3 it would appear that at room temperature nickel plating decreases the number of flexure cycles to conductor failure. At -162°C wires #1, 2, 8, 12, 13 and 14 fail quickly. From Figure 16-1 it is apparent that these wires are brittle as measured by the mandrel flexibility test at -196°C.

The increase in flex life for Wires #9 and 10 and to a lesser extent for Wires #4, 5, and 11 is more difficult to explain. It may be postulated that in these cases the insulation did not influence the failure and that the fatigue performance of the conductor is improved at the low temperature.

In over-all conclusion considerable information about the insulation is obtained most easily with the mandrel flexibility test. However, the repeated flexure test may need to be used to evaluate the performance of the conductor itself. At low temperatures brittle insulation may contribute to early conductor failure.

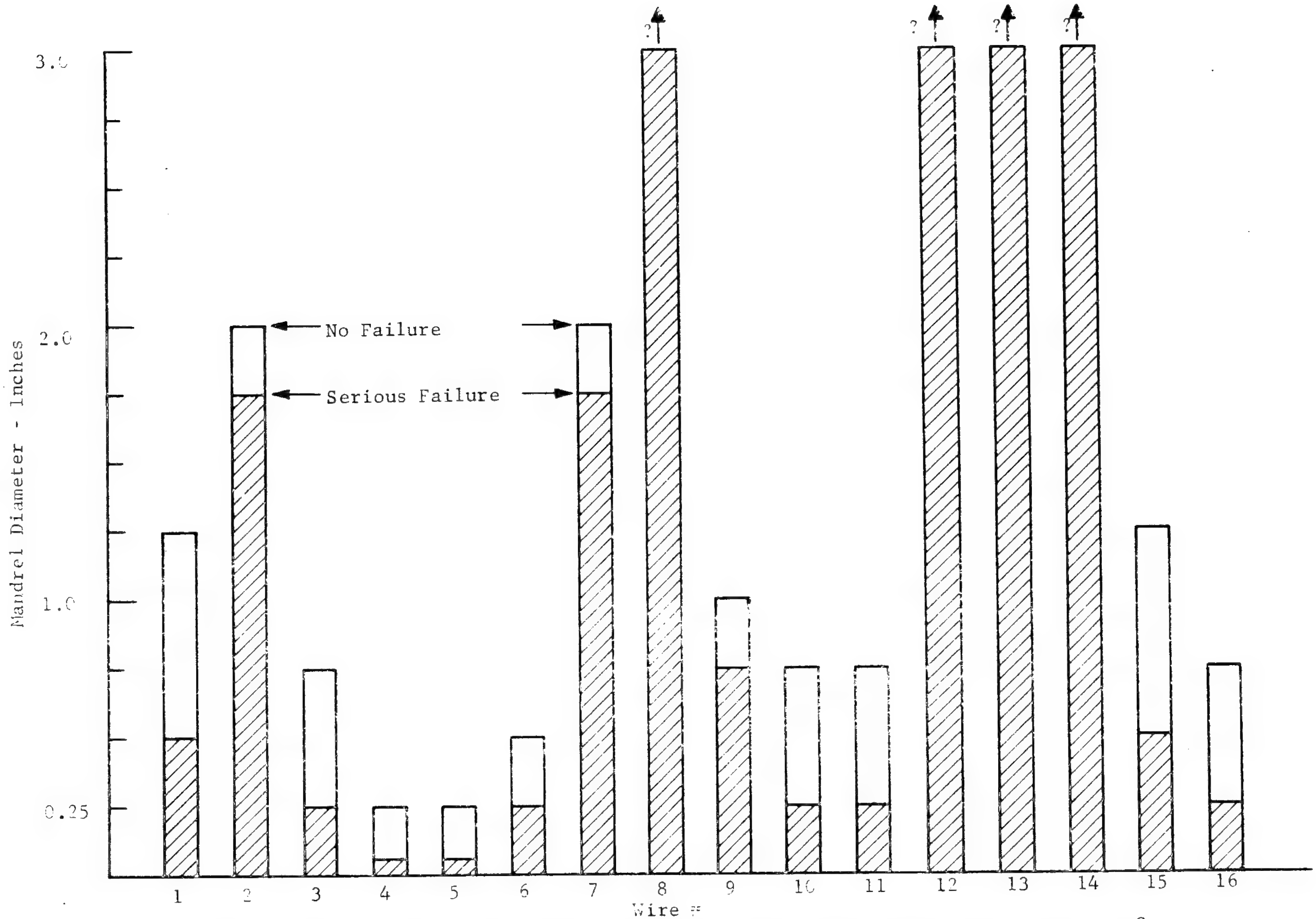

Figure 16-1 - Mandrel Flexibility of Unaged Wires - Tested in Liquid Nitrogen at -196°C

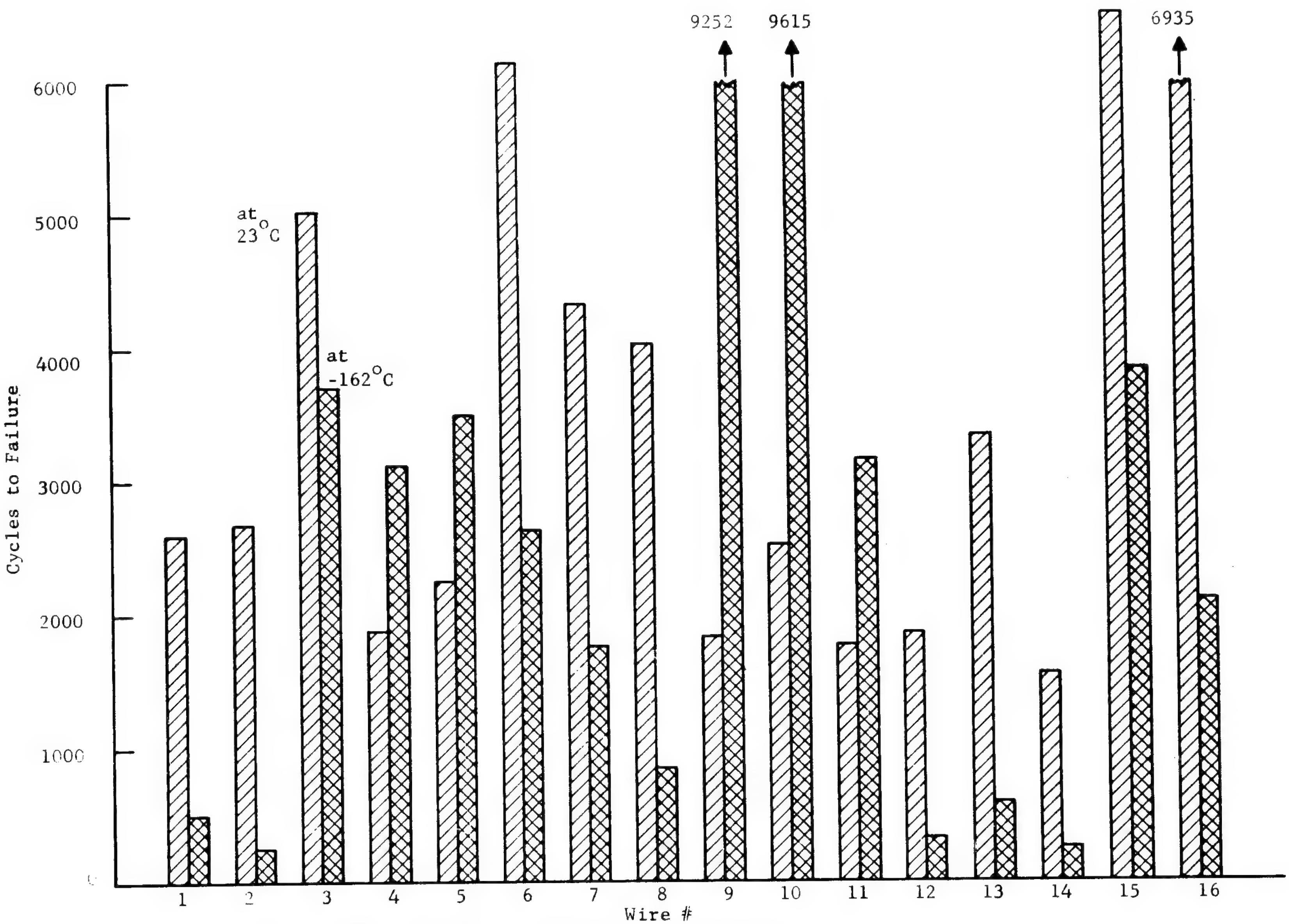

Figure 16-2 - Conductor Failure after Repeated Flexure
Comparison of Tests at 23°C and at -162°C

17. Scrape Abrasion

Many factors influence the abrasion of hook-up wire some of which can be listed as follows:

a. Nature and homogenity of the insulation

b. Wire size and insulation thickness

c. Nature and size of the abrading member

d. Load between abrading member and wire

e. Ambient, particularly temperature

Many kinds of abrasion tests have been tried, but usually the effect of important test variables has been neglected. Unfortunately, it is time consuming and expensive to adequately investigate so many variables. In this program only one wire size was involved and the insulation thickness was a functional variable included in the nature of the wire insulation. The back and forth motion of the needle in the repeated scrape abrasion test was considered to represent the "sawing" action of a wire against a relatively sharp metal edge. This action was considered more damaging than the action of one wire rubbing on another. The effect of needle diameter - an important variable - was not investigated. The effect of ambient was also unfortunately not investigated although to some extent this problem is evaluated by the cut-through and creep tests.

The effect of load was quite thoroughly investigated. In a surprising number of cases - 8 out of 14 - a power function described the results found as follows:

$$S = \frac{K}{p^n}$$

where S = scrapes to failure

p = load in grams

K = constant

n = power function

The results taken from log-log plots of scrapes to failure against load are summarized in Table 17-1. The tremendous range of results - from 2.5 strokes for silicone rubber (Wire #12) to 170,000 strokes for TFE Teflon (Wire #9) is

startling. When the significance of the power function - n - is recognized, its range is large too. The physical reality of a power function is difficult to grasp. The last column in Table 17-1 shows the factor by which the abrasion is decreased for a doubling of the load. This value ranges from 545 or ($2^{9.1}$) for Wire #2 and 8 or (2^3) for Wire #11. As greater ratios of loads are involved, the effect on the abrasion resistance becomes extremely large, particularly for Wires like #2. Obviously, to attain a significant understanding of abrasion resistance, it is absolutely essential to evaluate the effect of load. In Table 17-1 two values of slope-n are given for Wires #5, 8, 15 and 16 which are calculated from the non-linear values at the 3 loads for these wires in a rather questionable fashion. More data at more loads is needed for these wires. For Wires #13 and 14 only two test loads were used so that the calculation of slope is not warranted.

Some important observations about the abrasion resistance of the different types of wires can be summarized as follows:

a. The abrasion resistance of TFE Teflon (Wire #9) is outstanding particularly at light loads.

b. The poorly adhered ML overcoating over FEP Teflon (Wire #1) causes very poor resistance to abrasion. The well adhered ML overcoat on Wire #2 provides excellent abrasion resistance, but not as good as TFE Teflon alone.

c. The heavy TFE dispersion coating on Wire #3 results in excellent abrasion resistance.

d. The somewhat thinner Teflon dispersion coating on LEM Wires #6, 15, and 16 also appears to provide good abrasion resistance.

e. Very thin FEP H-film taping alone (Wire #4) possesses relatively poor abrasion resistance.

f. The fused FEP tape overcoating in Wire #11 results in extremely poor abrasion resistance. It can be easily scraped away with the fingernail also.

g. The abrasion resistance of silicone rubber (Wire #12) is extremely poor.

In over-all conclusion, the repeated scrape abrasion test can be used in excellent discriminatory fashion to evaluate the abrasion resistance of a wide range of hook-up wire insulations. The test is particularly useful because the important effect of load can be evaluated. However, for specification purposes the effect of wire diameter as well as insulation thickness needs to be determined. The effect of needle diameter should also be investigated. In acceptance testing, considerable variation may be expected and such variability must be factored into specification limits.

TABLE 17-1

RESISTANCE TO SCRAPE ABRASION

Wire #	Calculated Strokes at 500 Grams to Cause Failure	Calculated Slope-N for Scrape versus Load Curve	Factor for Doubling Load
1	approx. 500	about 9	520
2	20,000	9.1	545
3	23,000	6.3	78.5
4	220	4.0	16
5	1500	4.3 and 6.9	19.5-120
6	10,500	5.9	60
7	approx. 1500 (?)	6.1	69
8	6500	2.4 and 6.5	5-90
9	170,000	7.4	180
10	380	3.9	15
11	35	3.0	8
12	2.5	5.2	36
13	est. 450 (?)	-	-
14	est. 170 (?)	-	-
15	8500	4.1 and 7.2	17-145
16	12000	3.6 and 7.4	12-170

18. Blocking

The only cases of blocking that were observed occurred at elevated temperature with the polyolefin insulation wires. At 150°C, some blocking occurred with Wire #7 under the heat-shrinkable tubing that was used to hold the specimens together. Similar effects were observed with Wire #8 at 150°C in oxygen and vacuum. Wires could not be separated without tearing the insulation in the region that had been compressed by the heat-shrinkable tubing.

19. Cut-Through

The results of the cut-through tests are summarized in Figure 19-1 for 23°C and in Figure 19-2 for 149°C. The data clearly show the superior cut-through strengths of the H-film construction at both temperatures. The ML coatings of Wires 1 and 2 provide some improvement in cut-through strength over that of plain TFE (Wire #9), but these wires are still inferior to the H-film constructions.

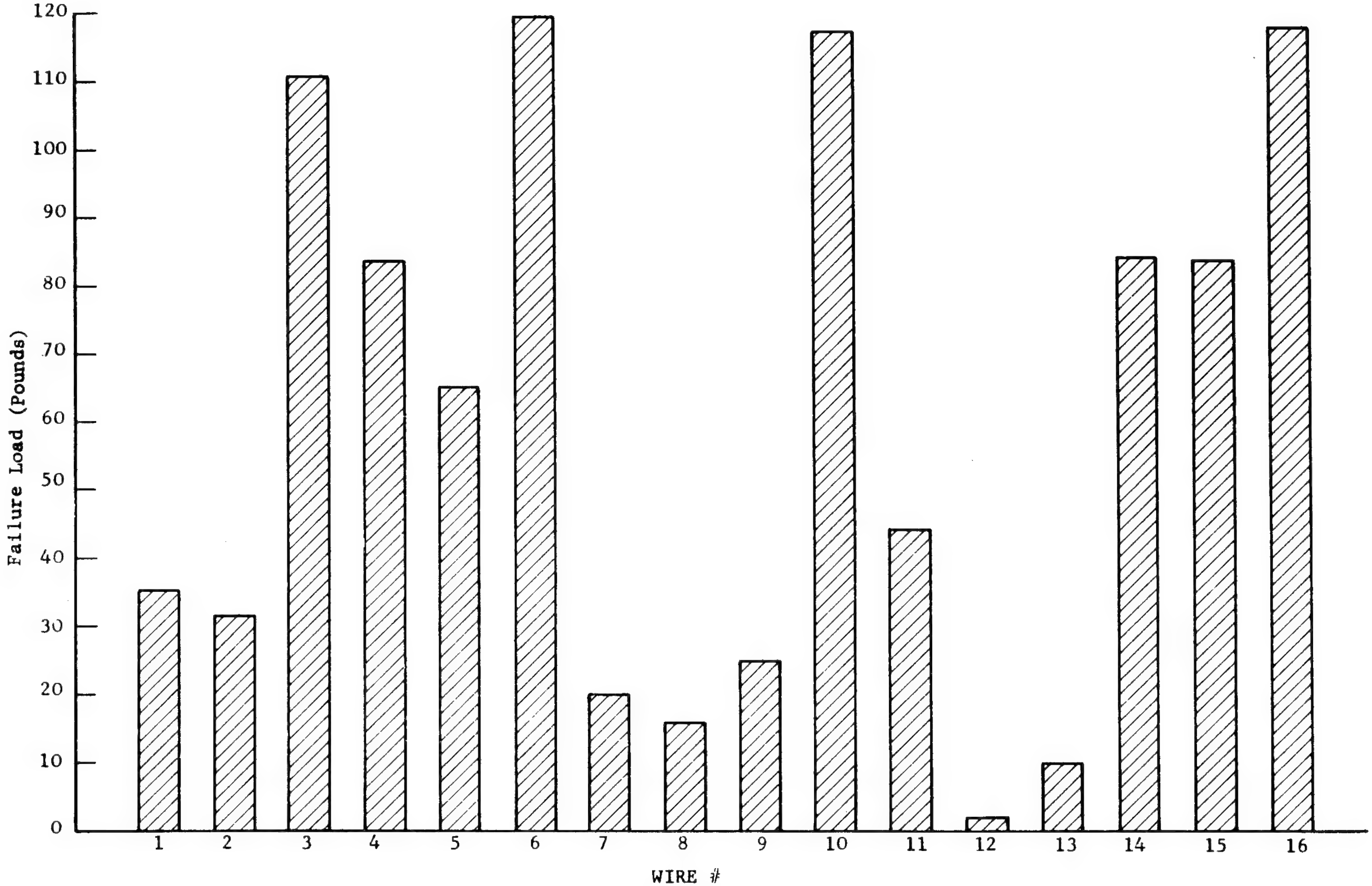

Figure 19-1: Comparison of Cut-Through Failure Loads at $23^{o}C$

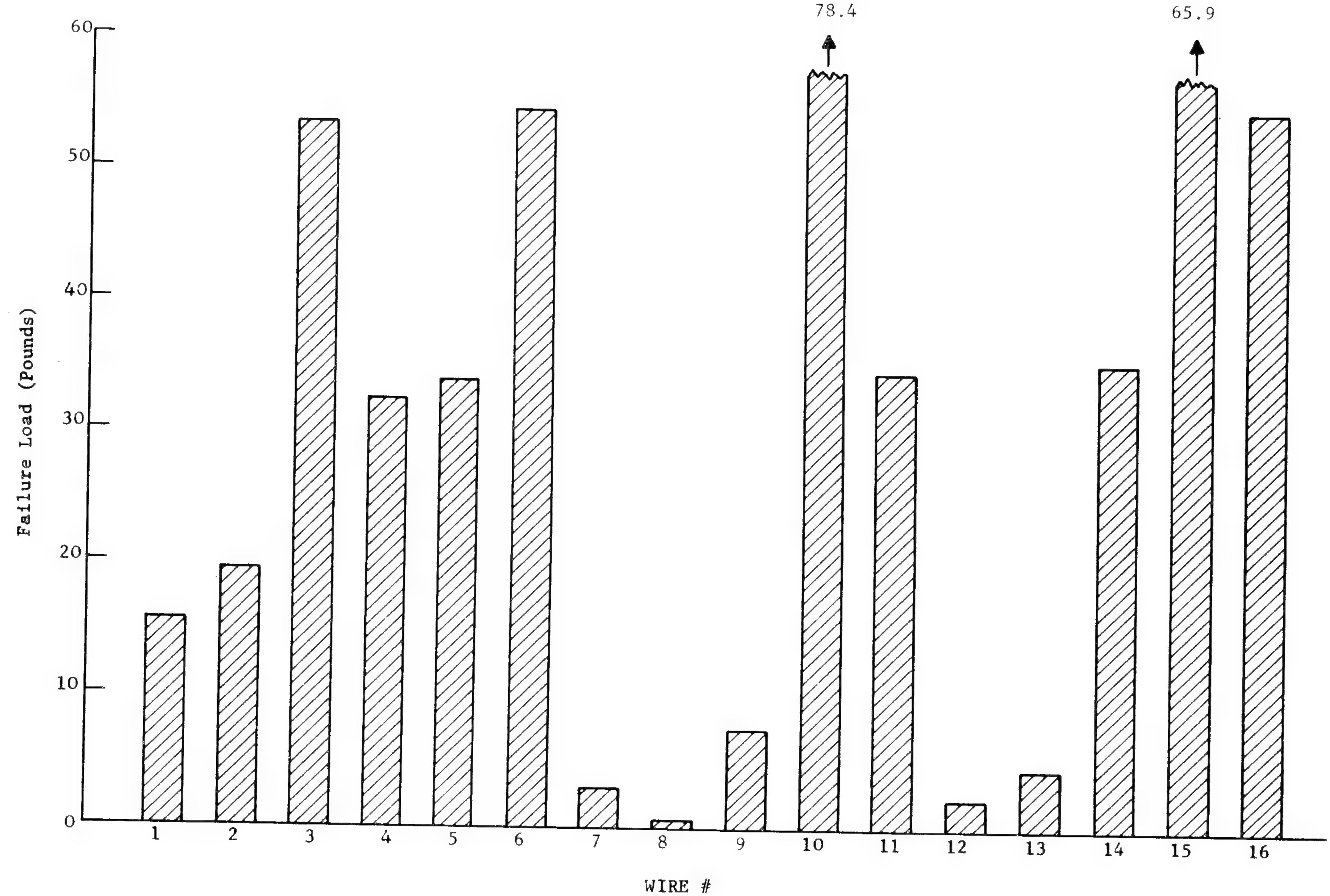

Figure 19-2: Comparison of Cut-Through Loads at 149°C

20. Thermal Creep

The one-hour failure loads for Type E Teflon (Wire #9) were established as 116 pounds at 23°C and 33 pounds at 149°C. Wires 7, 8, 12, 13 and 14 failed in shorter times than one hour when the standard loads were applied. Wires 1 and 2 were comparable to Wire #9, but the ML coating did not significantly improve their creep characteristics.

A modified test procedure was used to test the H-film construction because their superior cut-through strengths would permit them to withstand the standard loads for unreasonably long periods of time. From the detailed data given in Volume I, estimates of the one-hour failure loads were made. These values are summarized in Table 20-1.

In conducting the creep tests on the H-film wires, a short-time failure load was determined for each wire by applying an increasing load at a steady rate of .002 inches permminute. The fixed load for the first creep test was then taken as 75% of the short-time failure load. It is suggested that such a short-time measurement could be used as a screening test in future evaluation programs. Long-time tests would then be conducted only on those wires that exhibited short-time failure loads greater than a prescribed value. This minimum level could be readily determined for any wire size and general construction type.

TABLE 20-1

THERMAL CREEP

Estimated One Hour Failure Loads (Pounds)

Wire #	23°C	149°C
1	105-110	<25
2	100-110	40-45
3	300-325	110-130
4	160-170	85-100
5	210-275	90-100
6	410-425	225-240
9	116	33
10	275-300	225-240
11	175-180	70-90
15	185-200	125-140
16	350-370	170-180

21. Wicking

Measurements of wicking were made on six inch specimens that were dipped in a fluorescent dye solution to a depth of two inches. Wicking length was measured from the end of the specimen, so values less than 2 inches indicate that the solution did not even penetrate along the conductor as far as the liquid level. Only the polyolefin wires (#7 and #8) exhibited such resistance to wicking, as shown in the following summary:

Wicked 1/8" to 1/4"	Wicked 2" to 3"	Wicked 3" to 5"	Wicked 6"
7	2	1	3
8	9	5	4
	11	6	10
	12		15
	13		16
	14		

All of the extruded wires with the exception of Wire #1, wicked for less than 3". The taped construction, with the exception of Wire #11, do not exhibit resistance to wicking. This is to be expected because of the absence of a bond between the insulation and the conductor.

Weight gain data did not correlate well with wicking length measurements. Moisture absorption and adsorption increase the insulation weight even when no wicking occurs. The fluorescent dye technique is a more effective means of detecting wicking.

22. Thermal Aging

Aging effect in vacuum and 15 psia oxygen after 15 days at 150°C are detected onlyby the very sensitive mandrel flexibility test made in liquid nitrogen at -196°C. Only the slightest onset of aging is noted except for Wires #1, 7 and 8.

Neither voltage breakdown nor insulation resistance detect significant changes in thermal aging for the wires evaluted except for a small decrease in voltage breakdown for Wires #1 and2 when aged in vacuum.

23. Ultraviolet Radiation

Ultraviolet radiation appears to have little if any effect in increasing the effect of aging in vacuum. In fact, the 30 day aging in combined UV and vacuum is longer than the 15 day aging in vacuum described in Section 22.

In sharp contrast, the combination of ultraviolet radiation and oxygen produces startling degradation even at 95°C whereas without radiation almost no effect was noticed. It is probable that oxygen radicals and also ozone are created and are responsible for the damage. In particular ML enamel over Teflon, the bond between H-film and FEP Teflon, Kynar and the irradiated polyolefin are adversely affected.

It should be recognized that the combination of ultraviolet and oxygen is not likely to be encountered in spacecraft applications. Nevertheless the degradation obtained is interesting from the theoretical point of view and serves as a warning in case such exposure is contemplated.

24. X-Ray Irradiation

The very low levels of x-ray irradiation required in this program as expected have not induced significant change or deterioration in any of the Wires #1 through 14, except possibly for a decrease in voltage breakdown of Wire #1 when irradiated under vacuum.

The slight possibility that x-ray irradiation in oxygen might cause active species which could cause attack is not borne out at the radiation intensity and times involved.

25. Flammability

Few subjects are more controversial then the evaluation of flammability. Many variables are involved and many methods of test have been proposed. The test results have been even more variable than the tests and often have been of questionable value.

For spacecraft wire several basic factors appear to be important in establishing a functionally significant, flammability test:

1. The effect of ambient - atmospheric composition, temperature, relative gas volume and movement, etc.
2. Proximity to hot elements - by design or accident.
3. Short circuit currents which may very quickly raise the wire temperature to a very high temperature and even fuse the conductor.
4. Overload currents which cause the insulation to "cook" at an elevated temperature.

The argument may be made that short circuit current capability sufficient to fuse the wire is not available in spacecraft but such argument may be questioned and at any rate is beyond the scope of the subject work. It is important to make sure so far as feasible that the "worst" practical combination of test parameters is employed without being unrealistically severe.

While continuous fire and flame are the ultimate end-point of a flammability test many other precursor and concurrent phenomena are important including:

1. Change in the character of the wire insulation such as color, physical integrity, etc. for both operational reasons and the psychological effect on human operators.
2. Change in electrical characteristics including the functional capability of the insulation and the resistivity of the conductor.

3. Production of smoke and non-visible vapor which may adversely effect the operation of associated electrical, mechanical and optical devices directly or by condensing on critically important surfaces. Smoke and vapor may also produce toxic or adverse psychological reactions on human operators. Conversely, visible smoke may serve as a warning of malfunction to both human operators or protective devices.
4. Scintillation, sparking, flashing and other limited "fire" characteristics which are not continuous or progressive. Such effects usually occur in the evolved gases. They indicate the possibility of continuous flame and fire under a different balance of ambient, gas movement, relative volumes of flammable gas and oxidizing atmosphere, etc.

Finally it is most important that a spark or other high temperature source of ignition should be available in the flammability test. While it is recognized that in practice such ignition sources are avoided, it is possible that they may occur accidentally, i.e., the spark or arc associated with the fusing of a shorted wire on the malfunction of an electrical device.

To attain all of the foregoing in a practical flammability test is impossible but the concepts serves as a guide for a useful compromise. The approach taken to flammability testing is described under the test procedure and meets many of the foregoing requirements. In relatively minor ways improvements have been made particularly in temperature measurement as the work progressed. The experience obtained has provided the necessary background for making important improvements in test specimens, test equipment, and procedures which will be outlined later.

In this summary, details should not be included and for them reference may be made to the voluminous report in Volume I which is in itself a considerable condensation of the actual test data. In order to provide a quick broad summary and comparison of flammability results, Table 25-1 has been included. Even this single chart must be carefully studied and four additional charts, Figures 25-1 through 25-4, have been included to help visualize the results.

The results for three kinds of flammability tests designed to meet the three types of operational situations described earlier are reported in Table 25-1 and the Figures. Only those wires which burned in test have been included. Very rare fires, which occurred with several of the other wires, have been described in Volume I but are neglected for simplicity in presentation here. Unfortunately, only fire and smoke points can be reported in this summary and reference must be made to Volume I for the much more complicated and varied physical changes observed.

Both values of current in the 20 AWG wire have been reported. Despite strenuous effort and considerable progress, the accuracy of the temperature measurements must still be questioned although they certainly can provide a semi-quantitative basis for comparison. It should be noted that conductor temperatures are measured. When the external heater coil is used, the internal insulation temperature may be much higher than that of the conductor which undoubtedly explains the low conductor temperature for ignition of silicone rubber (Wire #12). Current measurements provide a functional basis for comparison but do not directly indicate temperatures either. Sometimes very rapid and large changes in wire temperature occur with small changes in current near the fusing point of the wire. Even though the same size wire was used fusing current varied from about 55 to 63 amperes, with considerable variability for supposedly identical wires. Any attempt to reduce weight by slightly decreasing the size of the conductor will show quickly in the flammability tests!

When the results are reviewed it is apparent that tests made with the external heater coil are the most severe. TFE Teflon burned only when the heater coil was used. The fires in the H-film taped wires #15 and 16 are attributed also to the Teflon bond and protective coating since H-film taped wires #4 and 5 without a protective Teflon coating never burned. The comparison of the high current test is less conducive but two observations can be made.

a. With unjacketed wires a large volume of gas is obtained quickly with the high current test and as a result fire occurs more quickly in this fashion.

b. With jacketed wires the jacket may "trap" evolved gas with the progressively increasing current which subsequently bursts out and is emitted.

Although the IMP and silicone wires, both with and without jackets, burn more readily than TFE Wire #9 and the H-film insulated wires, it should be recognized that they were tested only under very severe test conditions including the oxygen atmosphere. The impression that Kynar jacketed polyolefin (IMP) Wire #7 could not be made to burn in normal air was investigated with results shown in Figure 25-5. In air wire #7 burns under about the same conditions as it does in oxygen on the basis of the somewhat limited tests to date!! It is very surprising that the unjacketed wire #8 appears to burn more readily in air than in oxygen and additional tests should be made. Finally, attempts to ignite the #8 wire in either air or oxygen without using the ignition spark or internal heater failed completely. Even with the more readily ignited wires, the spark is an essential part of the test.

The variations in smoke are also of interest. It should be recognized that a considerable quantity of condensible and probably toxic vapor is released by TFE Teflon (Wire #9) even though smoke was not visible in these tests. Considerably less condensate was noticed with Wires #15 and 16 and only a little visible smoke was noted. The polyolefin and silicone rubber produce copious amounts of smoke at relatively low temperatures.

Proposed Test Modification

In this program single wires mounted in a "free" position have been evaluated since this was the stated requirement in the RFP. It is obvious that such mounting gave the greatest access to the oxygen atmosphere to encourage ignition. A vertical mounted wire was used to promote the spread of flame. Curiously in many tests, including those with TFE Wire #9, the flame progressed down as well as up the test specimen. However, no quantitative means could be devised to evaluate the retention of mechanical and electrical capability during the flammability test. It is recognized also that one current overloaded wire in a wire bundle may adversely affect the performance of other

wires in the same bundle. Finally the tendency to ignition may also be influenced by the presence of other wires in a bundle. It is therefore strongly recommended that a bundled test specimen be considered with which electrical tests can be made during the course of current overload in flammability studies.

It is recognized also that wire size and construction (such as shielding) may greatly affect flammability performance and investigation of their factors is needed.

It is recommended that the wire (or wire bundle) be held under slight tension in test so that it cannot bow away from the ignition source as sometimes happened in the present program. Finally, a better means for measuring wire temperature in overcurrent flammability tests is needed and the problem should be studied further.

TABLE 25-1

AVERAGE CURRENT AND TEMPERATURE NEEDED TO START FIRE IN 5 PSI OXYGEN

	#7		#8		#9		#12		#13		#14		#15		#16	
	Amp.	°C	Amp.	°C	Amp.	°C	Amp.	°C	Amp.	°C	Amp.	°C	Amp.	°C	Amp.	°C
Heater Coil Energized	0	481	0	401	40	>60	0?	547	0	253	42	804	40(?)	664	40	654
High Current Alone	50	673	41	619	No fire		46	673	90	603	53	708	No fire		60	1034
Increasing Current Alone	38	500	38	637	No fire		Glow only 44	570	41	499	No fire		No fire		No fire	

Average Current and Temperature Needed to Produce Smoke in 5 PSI Oxygen

	#7		#8		#9		#12		#13		#14		#15		#16	
Heater Coil Energized	Heavy* Quickly		Heavy* Quickly		No visible Smoke		0	273	Heavy* Quickly		Heavy* Quickly		Very Little		Very Little	
High Current Alone	38	434	Heavy* Quickly		No visible Smoke		39	359	40	386	41	383	45	641	45	657
Increasing Current Alone	36	356	36	540	No visible Smoke		31	260	41	459	43	469	?		45	673

*Smoke occurred so fast that the associated temperature could not be recorded.

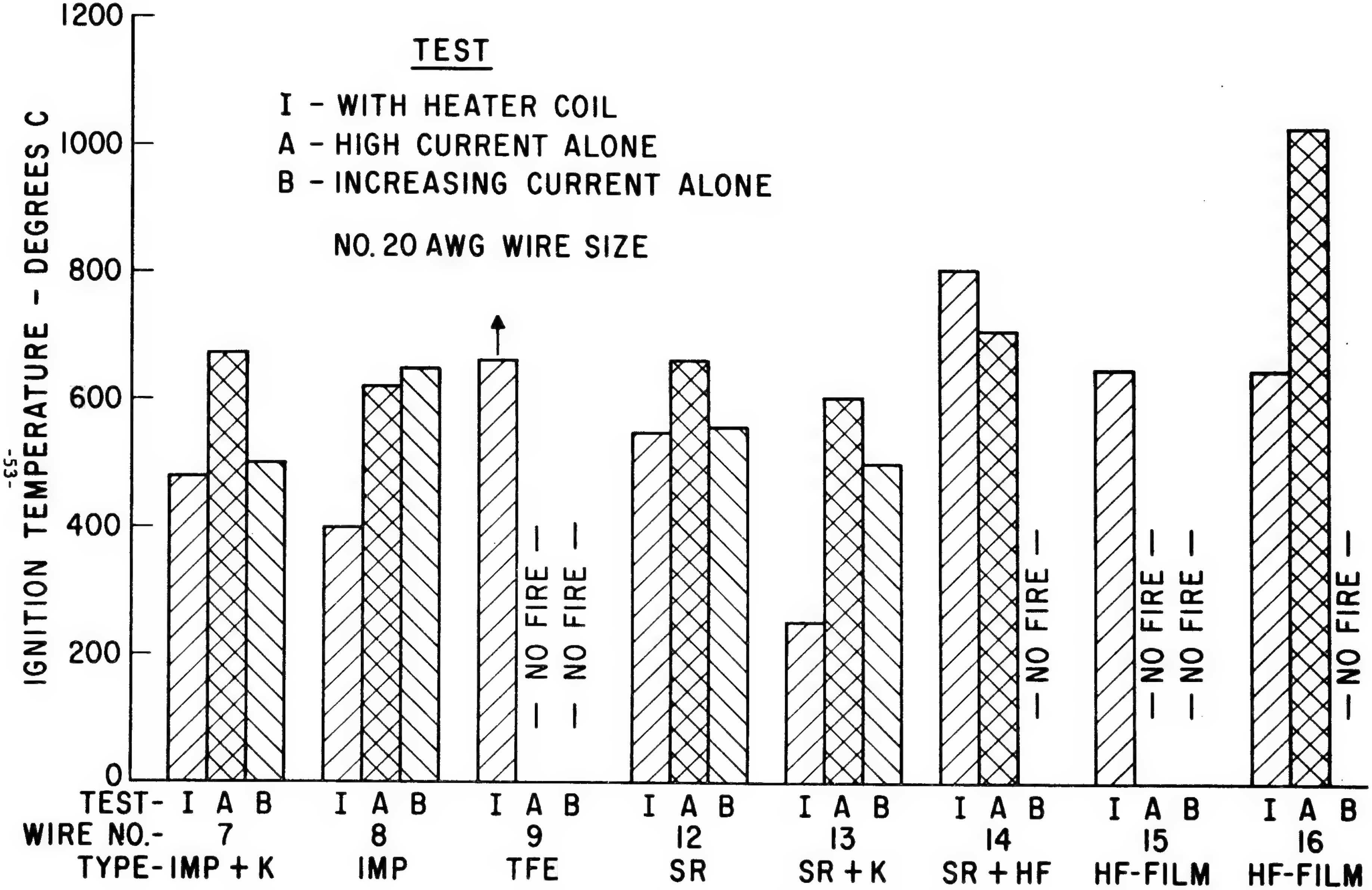

Figure 25-1 - Average Temperature Needed to Start Fire in 5 PSI Oxygen

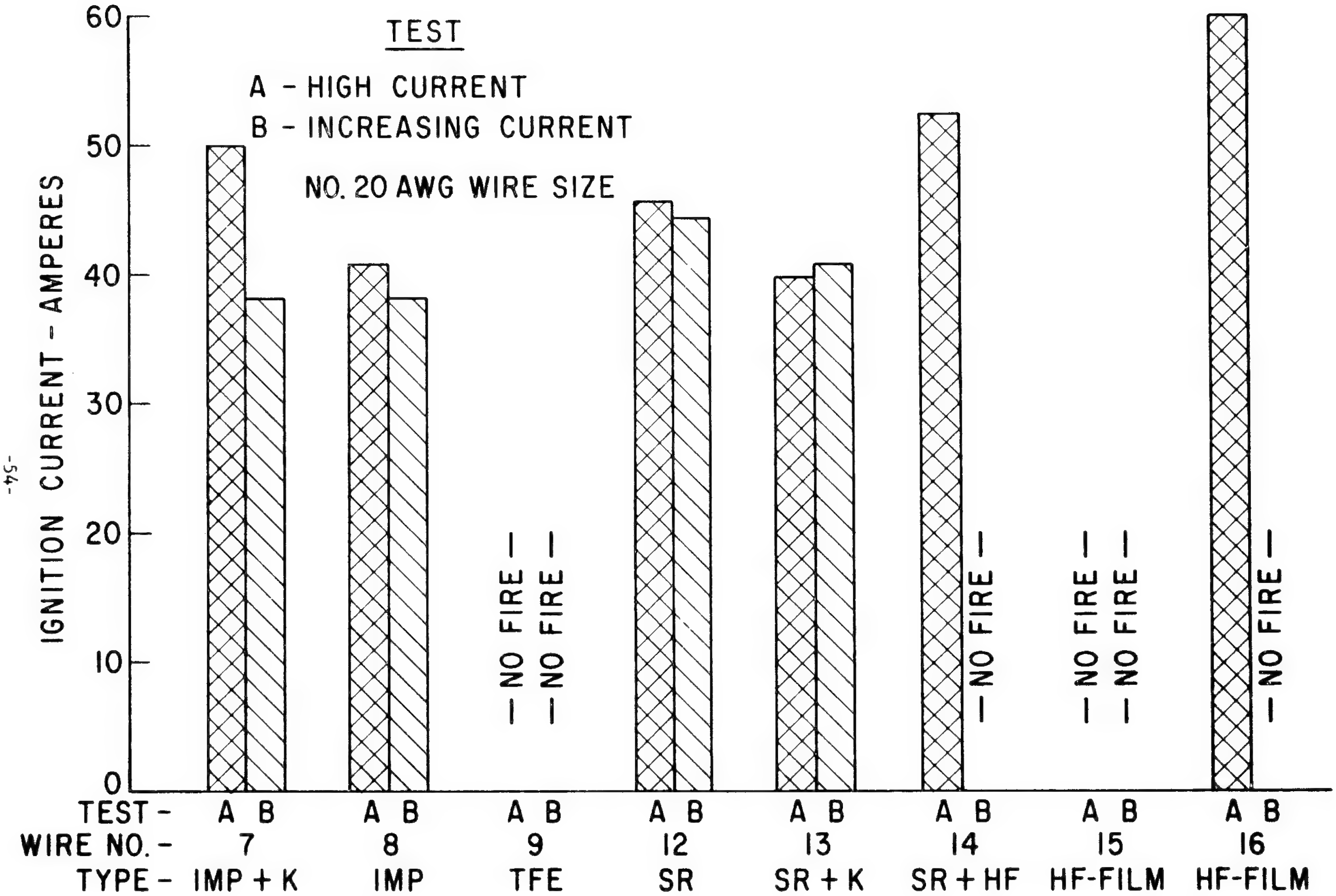

Figure 25-2 - Average Current Needed to Start Fire in 5 PSI Oxygen

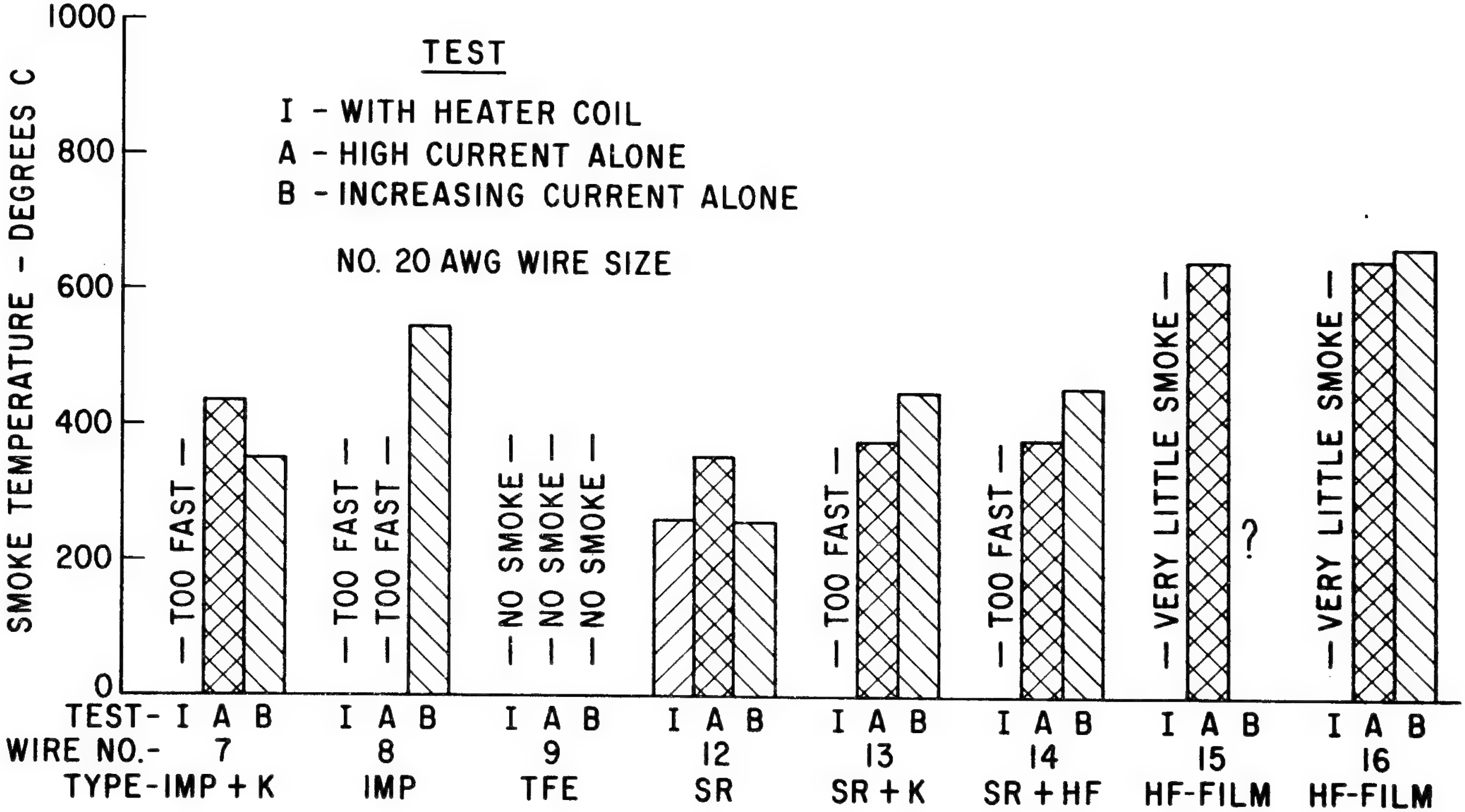

Figure 25-3 - Average Current Needed to Produce Smoke in 5 PSI Oxygen

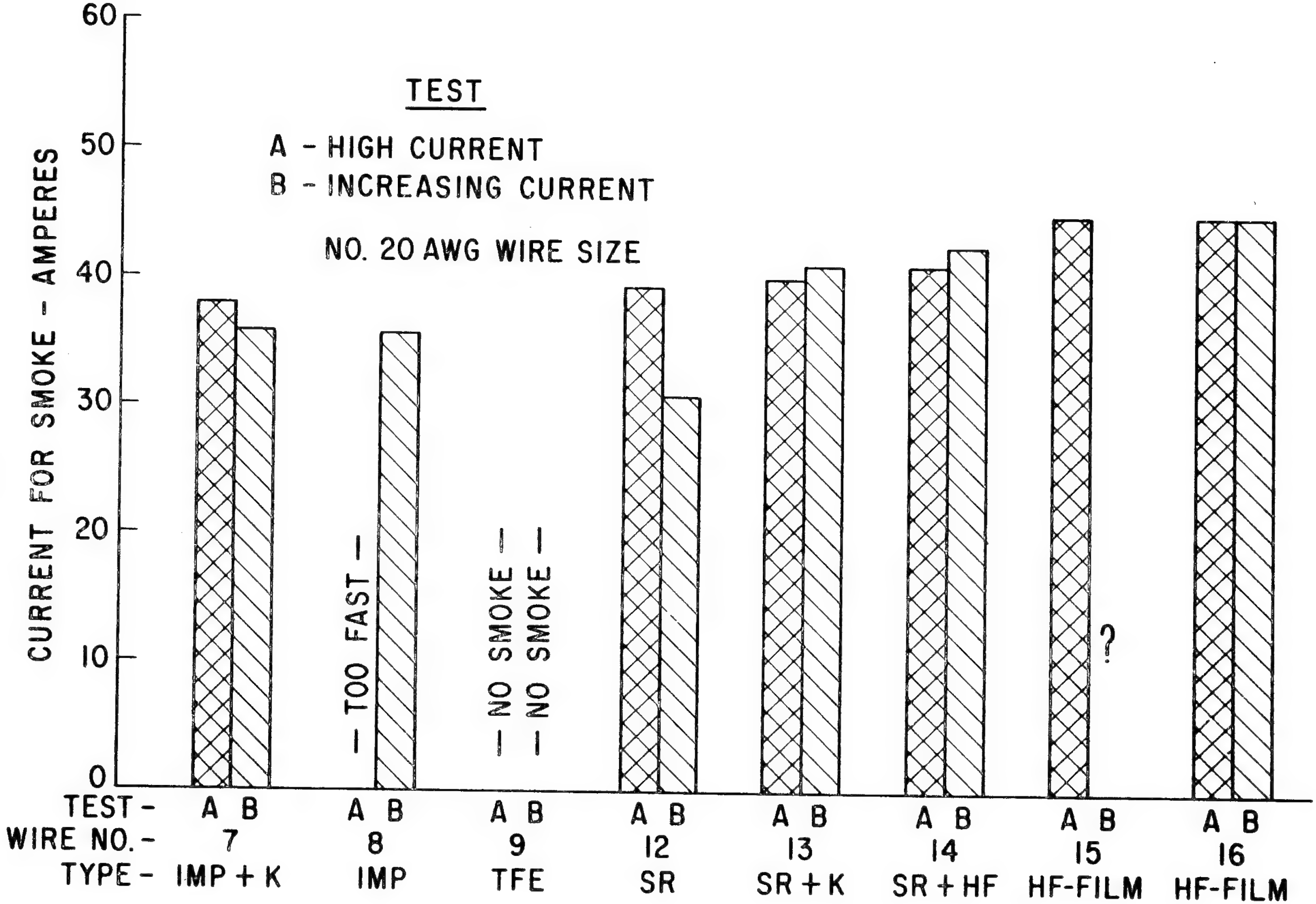

Figure 25-4 - Average Current Needed to Produce Smoke in 5 PSI Oxygen

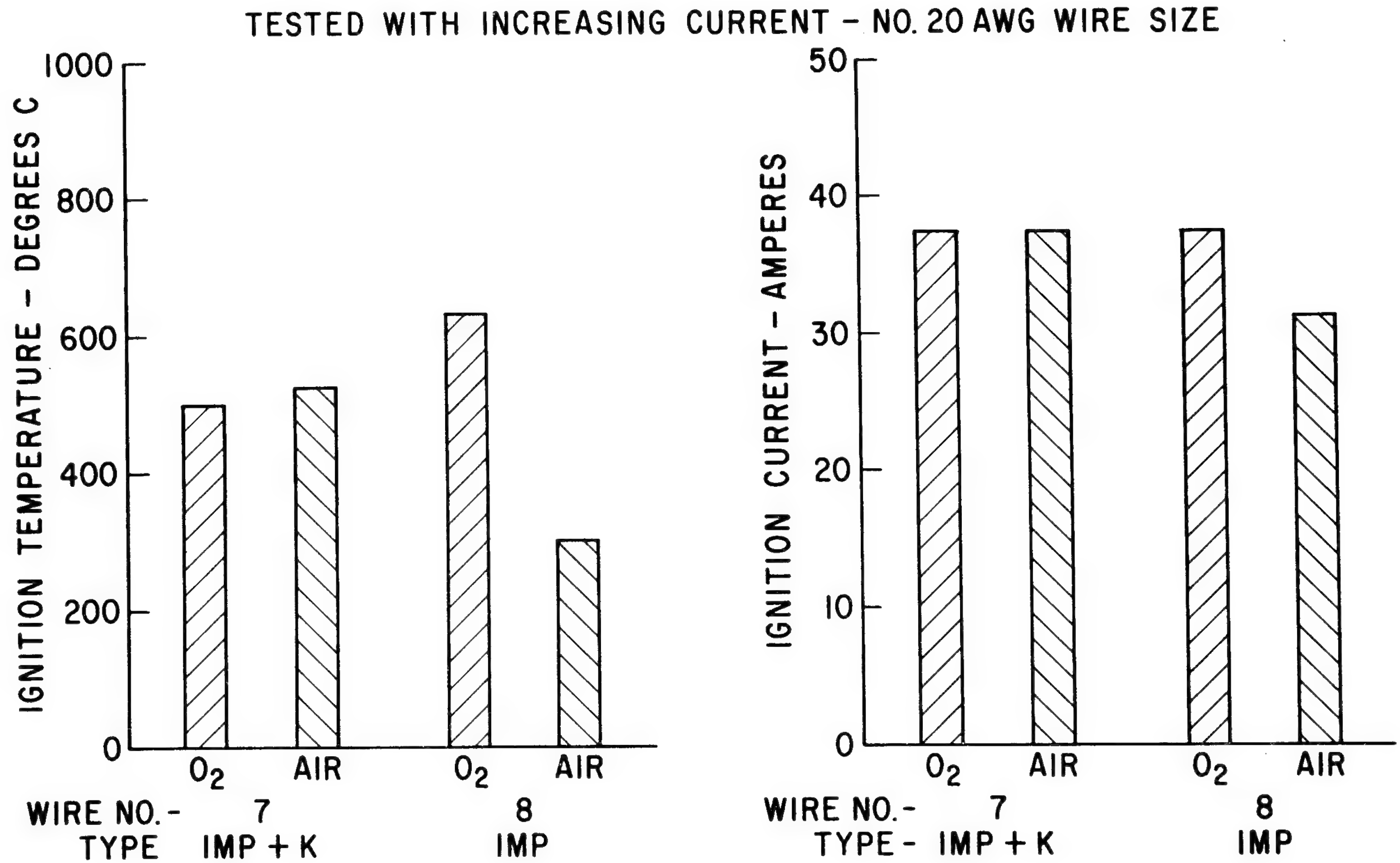

Figure 25-5 - Average Temperature and Current Needed to Cause Fires in 5 PSI Oxygen and in Air

26. Chemical Compatibility

From the application viewpoint two approaches may be taken to the problem of chemical compatibility.

a. With the use of a specific wire insulation, which contaminants must be avoided to avoid wire degradation?

b. Knowing the types of contamination which are to be expected or cannot be avoided, what type of wire insulation will be most resistant to degradation?

Both of these approaches will be taken in the following:

For this program the changes in mandrel flexibility, voltage breakdown and insulation resistance resulting from exposure to chemical contaminants have been used to quantitatively indicate attack. In many cases all three types of test indicate the attack. In some cases one or the other is sensitive to such changes while the others do not indicate degradation. Sometimes chemical exposure may improve the properties. For example, oils and solvents increase the voltage breakdown of silicone rubber, apparently by swelling it. This apparent improvement actually indicates degradation which might be measured by decrease in abrasion or cut-through.

In overall conclusion, it is apparent that extruded TFE Teflon (Wire #9) is resistant to all of the contaminants and in this respect is in a class by itself. The TFE Teflon dispersion overcoating on Wire #3 also provides excellent if not quite perfect protection. In contrast, silicone rubber is badly attacked by many of the contaminants although it is recognized that the silicone may recover its properties as the contaminant evaporates from it.

In the following, an overall comparison is given in qualitative fashion in summary tables as listed below:

Effect of Fuels and Oxidizers - Table 26-1
Effect of Oils, Salt and Glycol-Table 26-2
Effect of Solvents - Table 26-3

Where results merit a more quantitative treatment, bar graphs have been included, although for detailed results the summary of test results in Volume 1 of this report should be consulted.

Degradation from Fuels and Oxidizers

In summary Table 26-1 it is apparent that all of the fuels and oxidizers attack silicone rubber (Wire #12) and that TFE Teflon is essentially completely inert. All of the fuels and oxidizers tested attack H-film, but the attack of unsymmetrical dimethylhydrazine (UDMH) is moderate or small. The TFE Teflon dispersion overcoating on Wire #3 provides essentially complete protection to the underlying H-film except against nitrogen tetroxide (N_2O_4). The FEP coating on the H-film itself provides little protection for Wires #4 and #5. The FEP dispersion coating on Wire #6 provides some limited protection. The Kynar jacket over the irradiated modified polyolefin (Wire #7) appears to provide only limited protection and, in contrast, the Kynar jacket over silicone rubber increases the attack perhaps by trapping the contaminant at the interface between the jacket and the substrate.

The ML enamel* overcoat on wires #1 and 2 is also attacked, but the substrate Teflon is not attacked. Thus, whatever function the ML may serve is lost. On the other hand, flexibility at cryogenic temperatures is improved since the ML enamel affects such flexibility adversely.

The performance of Wire #6 (the LEM wire with FEP dispersion coating over FEP, H-film tape) and #8 (irradiated modified polyolefin) is shown in Figures 26-1 and 26-2. In Figure 26-1 the average value for the ratios of maximum and minimum values of breakdown voltage before and after exposure for 20 hours to the hydrazine type fuels and oxidizers. In Figure 26-2 the log (geometric) average for the ratio of maximum and minimum values of insulation resistance is plotted. It is apparent that the attack of UDMH and, in this case, MMH, is negligible with Wire #6. In contrast, these two fuels attach the modified polyolefin of Wire #8 with the greatest severity. Yet fluorine exhibits negligible attack on Wire #8.

In summary it may be concluded:

a. The attack of oxidizers and fuels is generally severe on silicone rubber, H-film and ML enamel.

b. UDMH is the least active of these hydrazine type fuels.

*The ML enamel, like H-film, is a polyimide polymer.

c. Teflon extrusion or adequate TEFLON overcoats must be used if the effect of fuels and oxidizers must be withstood. Note: The FEP Teflon layer on the H-film is not in itself adequate to prevent attack.

Degradation from Oils, Salt & Glycol Solutions

From summary Table 26-2 it is apparent that hydraulic oil and ethylene glycol solution attack silicone rubber and many of the solvents penetrate the taped and jacketed structures to cause a decrease in mandrel flexibility at cryogenic temperatures. This decrease in flexibility has functional significance only in very cold ambients. Generally the resistance of the wires to the class of contaminants under this heading is good. A notable exception is the degradation caused by exposure to salt-fog as summarized in Figure 26-3 and 26-4. The voltage breakdown of H-film taped Wires #4 and #5, as well as the modified polyolefin Wire #8 is markedly decreased. Examination of the H-film showed evidence of severe crazing on Wires #4 and #5 and some crazing in Wire #6 which was apparently partly protected by the FEP dispersion coating. It is believed that hydrolytic degradation of the H-film has occurred during the exposure to the salt-fog test. Similar crazing of the H-film did not occur in Wires #3, 10 or 11. Apparently the TFE dispersion coat (#3) and TFE fused tape (#11) prevented attack. The absence of attack with wire #10 after salt-fog exposure is surprising.

The decrease in voltage breakdown for the polyolefin Wire #7, after exposure to salt-fog (and also to NaCL solution) is probably attributable to direct moisture pick-up in the filled insulation. The absence of an associated decrease in insulation resistance cannot be explained.

In summary and conclusion, moisture and high temperatures in combination can produce embrittlement in H-film which can be prevented by adequate over-coating with Teflon. Silicone rubber is susceptible to oil and also to the water solution of ethylene glycol. A loaded polyolefin is susceptible to degradation from salt solution, but such attack is much decreased by a Kynar jacket over the polyolefin.

Degradation from Solvents

The effect of solvents is summarized in Table 26-3. The largest effects are noticed in the change of voltage breakdown with wires 7, 8, 12 and 13. These results are summarized in Figures 26-5 and 26-6. Insulation resistance has not been plotted because the changes are not particularly significant.

The most noteworthy changes occur in the increased voltage breakdown for Wire #7 and #8 after exposure to tricholoroethylene. (Similarly, the breakdown voltage of extruded TFE Teflon almost doubles.) Freon 113 has a similar, but less marked effect for the same wires. Halogenated solvents increase the voltage breakdown of air and thereby may provide an explanation for the increase in the twisted pair test specimen which most often do not fail electrically at the points of contact, but include some air space in the breakdown path. Curiously, acetone degrades unjacketed polyolefin Wire #8, but conversely degrades just the Kynar jacketed silicone (Wire #13). The irradiated Kynar jacket of Wire #7 appears to be undamaged by acetone, but the unirradiated Kynar jacket of Wire #13 exhibits severe physical attack from acetone exposure. However, the marked decrease in breakdown voltage for Wire #13 sill needs to be explained, since the degradation of the jacket alone could not account for so large a change. JP-4 degrades just the Kynar jacket wires, perhaps because it becomes trapped at the interface between jacket and substrate.

In summary and in conclusion, largely unpredictable and sometimes rather subtle changes occur after solvent exposure with the polyolefin and silicone based wires. However, degradation is not marked except for Wires #8 and #13 after exposure to acetone. In contrast, tricholoethylene exposure markedly improves the voltage breakdown of Wires #7 and #8. Based on these results it would seem wise to investigate the effect of the specific solvents likely to be encountered in service if polyolefin or silicone rubber insulated wire are used. Organic solvents of the types evaluated appear to offer no threat of degradation with Teflon or H-film insulation.

TABLE 26-1

SUMMARY, DEGREE OF DEGRADATION FROM EXPOSURE FOR 20 HOURS TO FUELS AND OXIDIZERS

		WIRE #													
Mat.	Test	1	2	3	4	5	6	7	8	9	10	11	12	13	14
UDMH	Flex.	*	*	None	Some	Some	None	Some	?	None	Some	Slight	NT	?	Slight
	Bd.	None	None	None	Some	None	None	Some	Severe	None	None	None	Some	Severe	None
	IR	None	None	None	Some	Some	None	Some	Severe	None	Some	None	Some	Severe	None
MMH	Flex.	*	*	None	Severe	Severe	Slight	Some	?	None	NT	Some	?	?	NT
	Bd.	None	None	None	Severe	Severe	Slight	Some	Severe	None	Severe	Some	Some	Some	Severe
	IR	None	None	Trace	Some	Severe	Trace	Some	Severe	None	Severe	None	Some	Severe	Severe
N_2H_4	Flex.	*	*	None	Severe	Severe	Slight	Some	?	None	NT	Some	?	?	
	Bd.	None	None	None	Severe	Severe	Some	Some	Some	None	Severe	Severe	Some	Severe	Severe
	IR	None	None	None	None (?)	Severe	Some	Some	Some	None	Severe	Some	Severe	Severe	Severe
A-50	Flex	*	*	None	Severe	Severe	None	Some	?	None	NT	Some	?	?	NT
	Bd.	None	None	None	Severe	Severe	Some	Severe	Severe	None	Severe	Some	Some	Severe	Severe
	IR	Slight	None	Trace	Severe	Severe	Slight	Severe	Some	None	Severe	None	Severe	Severe	Severe
N_2O_4	Flex.	None	*	Some	Severe	Severe	Severe	Severe	?	None	Severe	Severe	NT	Severe	NT
	Bd.	Some	Severe	Some	Severe	Severe	Some	Some	Some	None	Severe	Some	NT	Severe	Severe
	IR	Some	Some	Some	Severe	Some	Some	Some	Some	None	Severe	Slight	NT	Some	Some
Flu-orine	Flex.	None	None	None	Severe	Severe	Slight	Some	?	Slight (?)	Slight	Some	Severe	NT	Severe
	Bd.	None	None	None	Severe	Some	**	None	None	None	Some	Some	**	**	Some
	IR	Trace	None	Trace	None	Some	Some**	None	None	None	Some	Trace	**	**	Some

* - Improved
** - Short Exposure - fire
NT - No test, severe damage
? - Specimen fails on 3" mandrel before exposure.

TABLE 26-2

SUMMARY, DEGREE OF DEGRADATION FROM CHEMICAL EXPOSURE FOR 14 DAYS TO OILS, SALT, ETHYLENE GLYCOL

		WIRE #													
Mat.	Test	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Lube Oil	Flex.	*	None	None	Some	Some	Trace	Some	?	None	None	Some	?	?	?
	Bd.	None	None	None	None	None	*	None	None	None	None	None	*	None	None
	IR	None	None	Trace	Trace	Slight	Trace	None	None	Slight**	Trace	Trace	Some	None	None
Hydraulic Oil	Flex.	*	*	None	Slight	Slight	None	Some	?	None	None	Some	NT	NT	?
	Bd.	None	None	None	None	*	*	None	*	None	None	*	None	None	None
	IR	None	None	Trace	Trace	Some	Trace	None	None	Slight	Trace	Trace	Trace	None	None
50% NaCl	Flex.	Trace	Slight	None	Slight	Some	None	None	?	None	None	Some	?	?	?
	Bd.	None	None	None	Some	Trace	None	Trace	Some	None	None	None	None	None	None
	IR	Slight	*	Trace	Trace	Some	Trace	None	None	Trace**	Slight	Trace	Trace	Trace	Trace
Salt Fog	Flex.	Some	Some	Slight	Severe	Some	Some	None	?	None	None	Trace	?	Slight	?
	Bd.	None	None	None	Severe	Severe	Some	Slight	Some	Slight	Slight	None	Slight	None	None
	IR	None	None	Slight	Some	Some	Slight	None	None	None	Slight	None	None	None	None
Ethylene Glycol Water	Flex.	Some	Some	None	None	None	None	Slight	?	None	Slight	Some	?	?	?
	Bd.	None	None	None	None	None	*	None	None	None	None	None	Some	Slight	None
	IR	None	Slight	Slight	Slight	Some	Some	None	*	None	Slight	Slight	Some	None	Slight

*Improved somewhat
**Damage indicated may not be significant.
?Fails on 3" mandrel before exposure.
NT-Too damaged to test.

TABLE 26-3

SUMMARY, DEGREE OF DEGRADATION FROM EXPOSURE FOR 14 DAYS TO SOLVENTS

Mat.	Test	WIRE # 1	2	3	4	5	6	7	8	9	10	11	12	13	14
Ethyl Alcohol	Flex.	Slight	Some	None	Some	Some	Slight	Slight	?	None	None	Slight	?	?	?
	Bd.	None	None	None	None	None	None	None	Slight	None	None	None	None	Slight	Slight
	IR	None	None	None	*	None	None	*	*	None	None	None	None	None	None
JP-4	Flex.	Slight	Slight	None	Slight	Slight	Slight	Slight	?	None	None	Slight	NT	NT	?
	Bd.	None	None	None	None	*	None	Some	**	*	None	None	None	Slight	None
	IR	None	None	None	None	Slight	Slight	*	*	None	Slight	None	None	None	None
Freon 114	Flex.	Slight	None	None	None	None	Slight	Slight	?	Slight	None	Some	?	NT	?
	Bd.	Slight	None	None	None	None	None	None	None	None	None	None	None	None	None
	IR	None	None	None	None	Trace	Trace	*	*	None	None	None	None	None	None
Trich-oloro-ethylene	Flex.	Slight	Slight	None	Some	Some	Some	Slight	?	None	Slight	Slight	NT	NT	?
	Bd.	None	None	None	None	None	None	*	**	*	None	None	None	None	*
	IR	*	*	None	None	Trace	None	*	*	None	None	None	Some	None	None
Acetone	Flex.	None	Some	Slight	Some	Slight	Slight	Slight	?	None	Slight	Some	?	NT	?
	Bd.	Slight	None	None	None	None	None	None	Slight	*	None	None	None	Severe	Some
	IR	None	None	None	None	Some	Slight	None	None	*	None	None	None	Some	None
Freon 113	Flex.	Slight	Slight	None	Some	Slight	None	Slight	?	Slight	Slight	Some	NT	NT	?
	Bd.	None	None	None	None	None	*	*	**	*	None	None	None	Slight	*
	IR	None	None	Trace	*	Trace	Trace	*	*	*	None	None	None	None	None

* - Indicates a varying degree of improvement.
** - Indicates considerable improvement.
? - Fails on 3" mandrel before exposure.
NT - Too damaged to test.

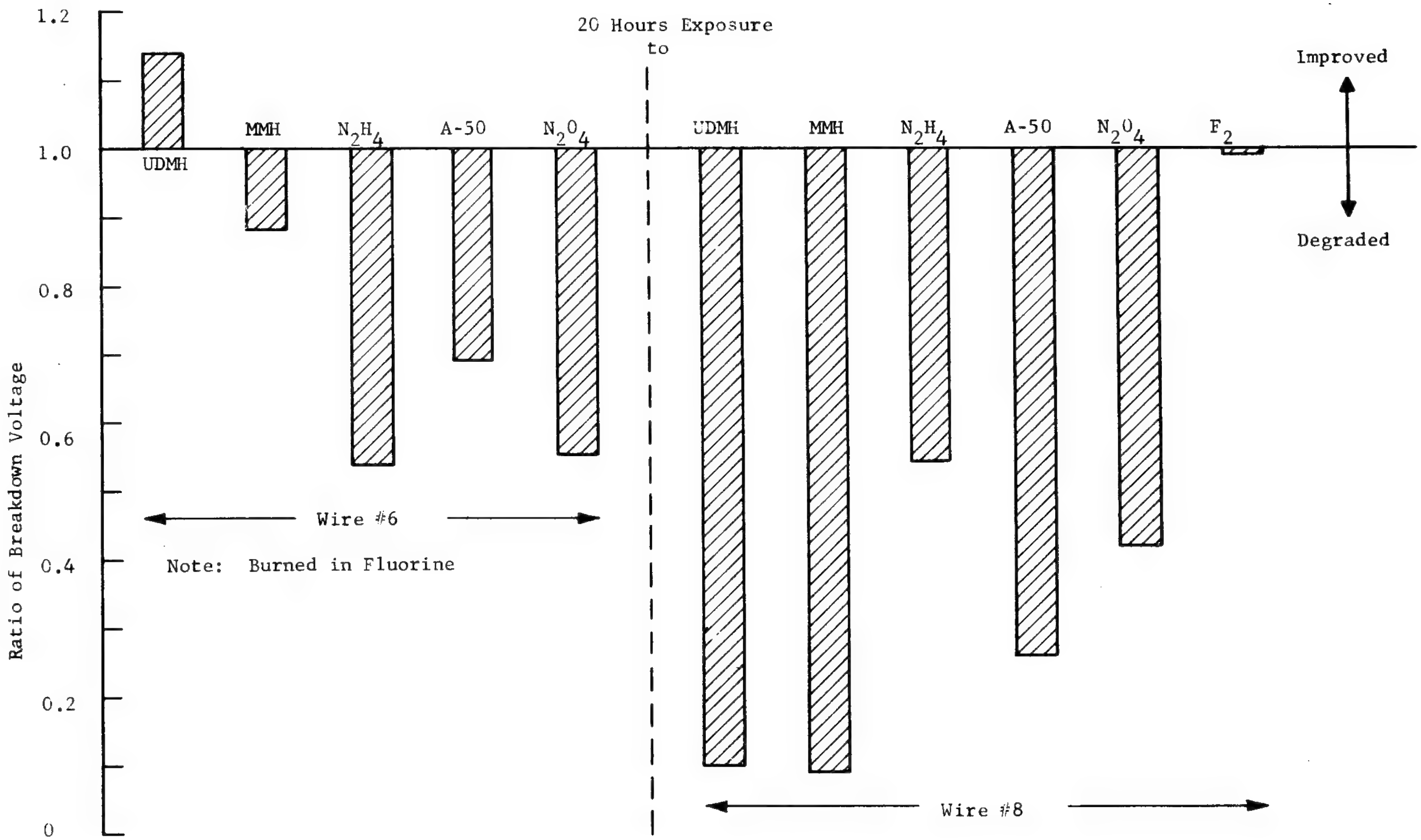

Figure 26-1 - Ratio of Breakdown Voltage - **Exposed to Unexposed**
Comparison of the Effect of Fuels and Oxidizers on Wires #6 and #8

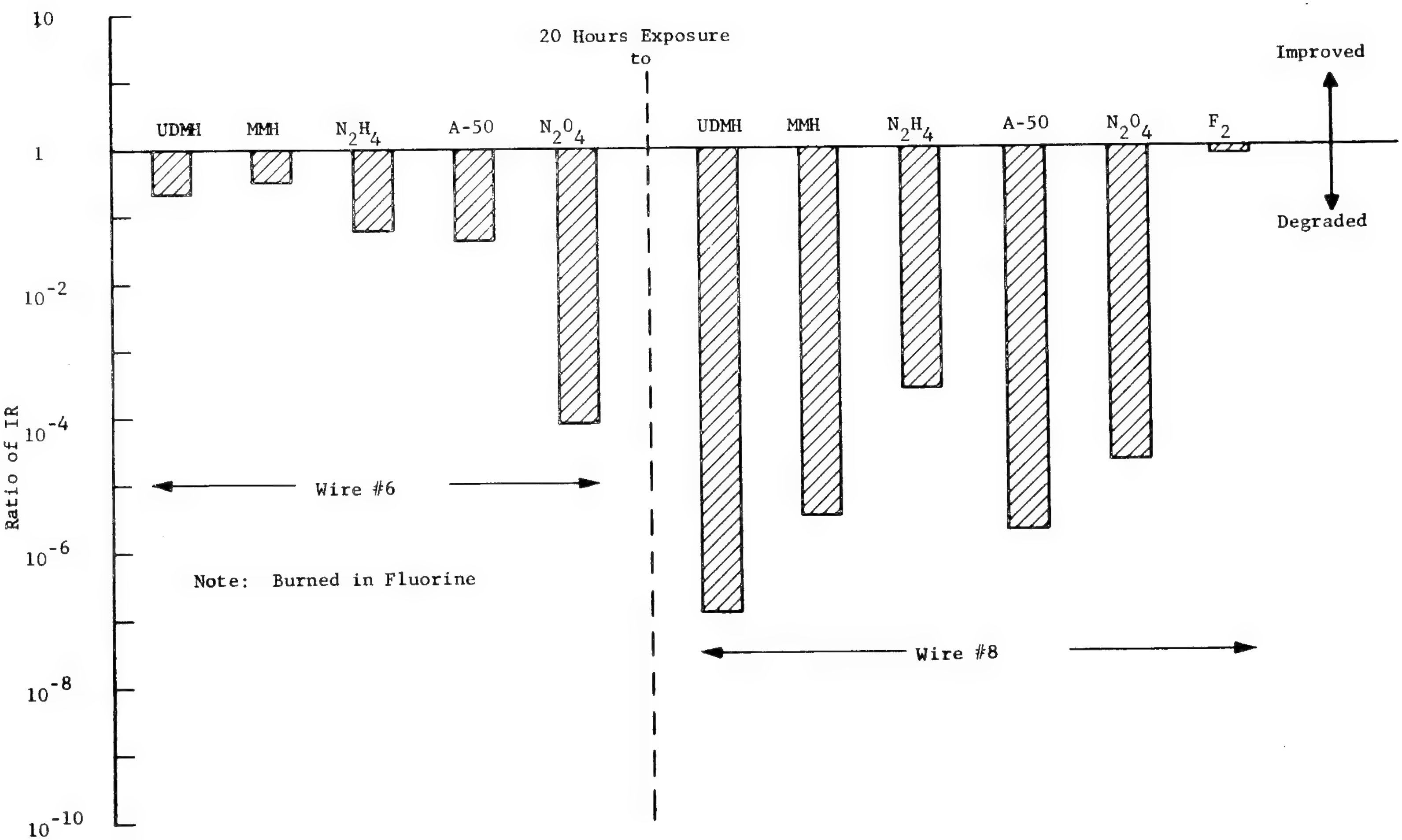

Figure 26-2 - Ratio of Insulation Resistance - Exposed to Unexposed
Comparison of the Effect of Fuels and Oxidizers on Wires #6 and #8

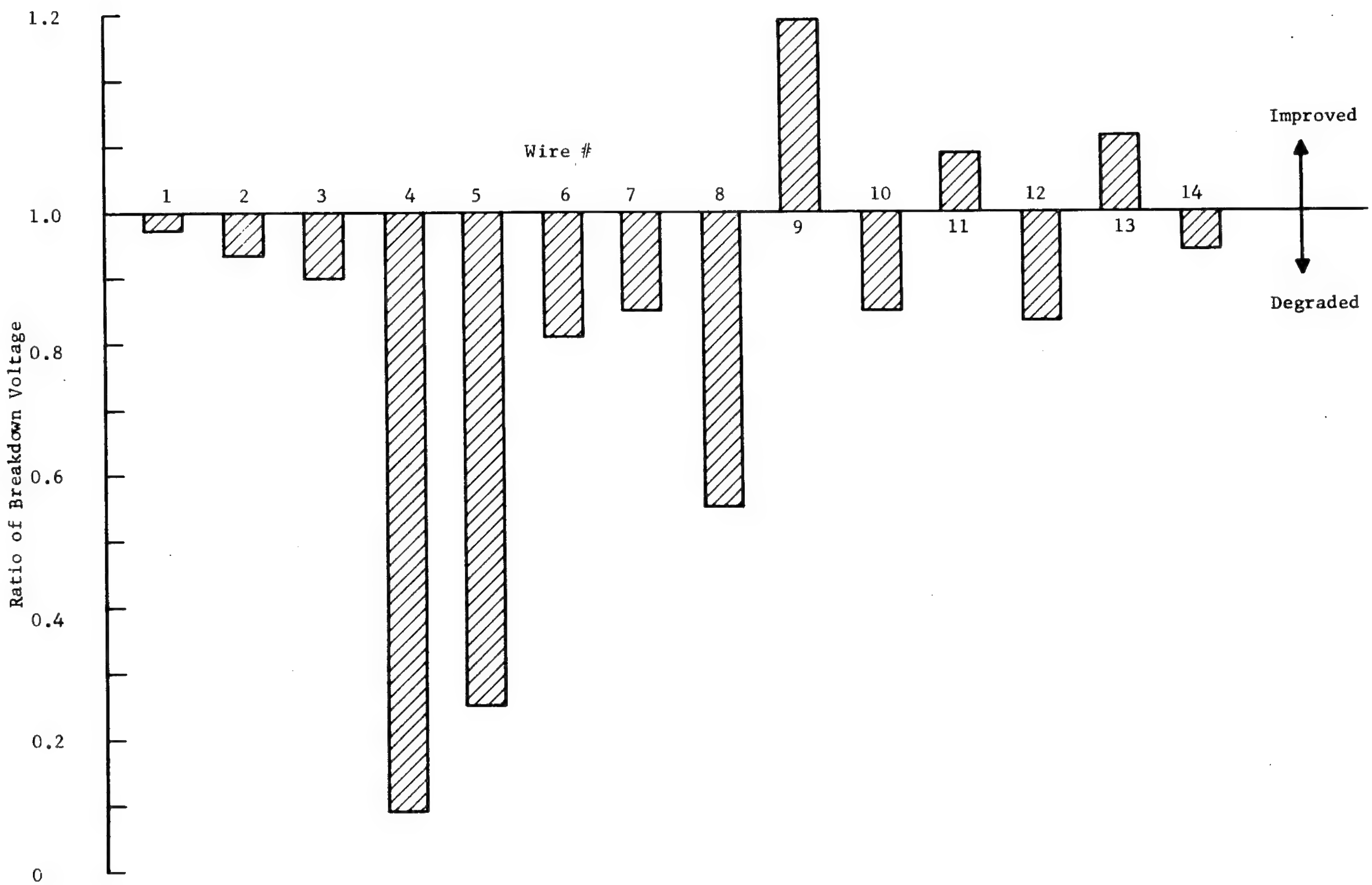

Figure 26-3 - Ratio of Breakdown Voltage - Exposed/Unexposed
14 Days in Salt Fog

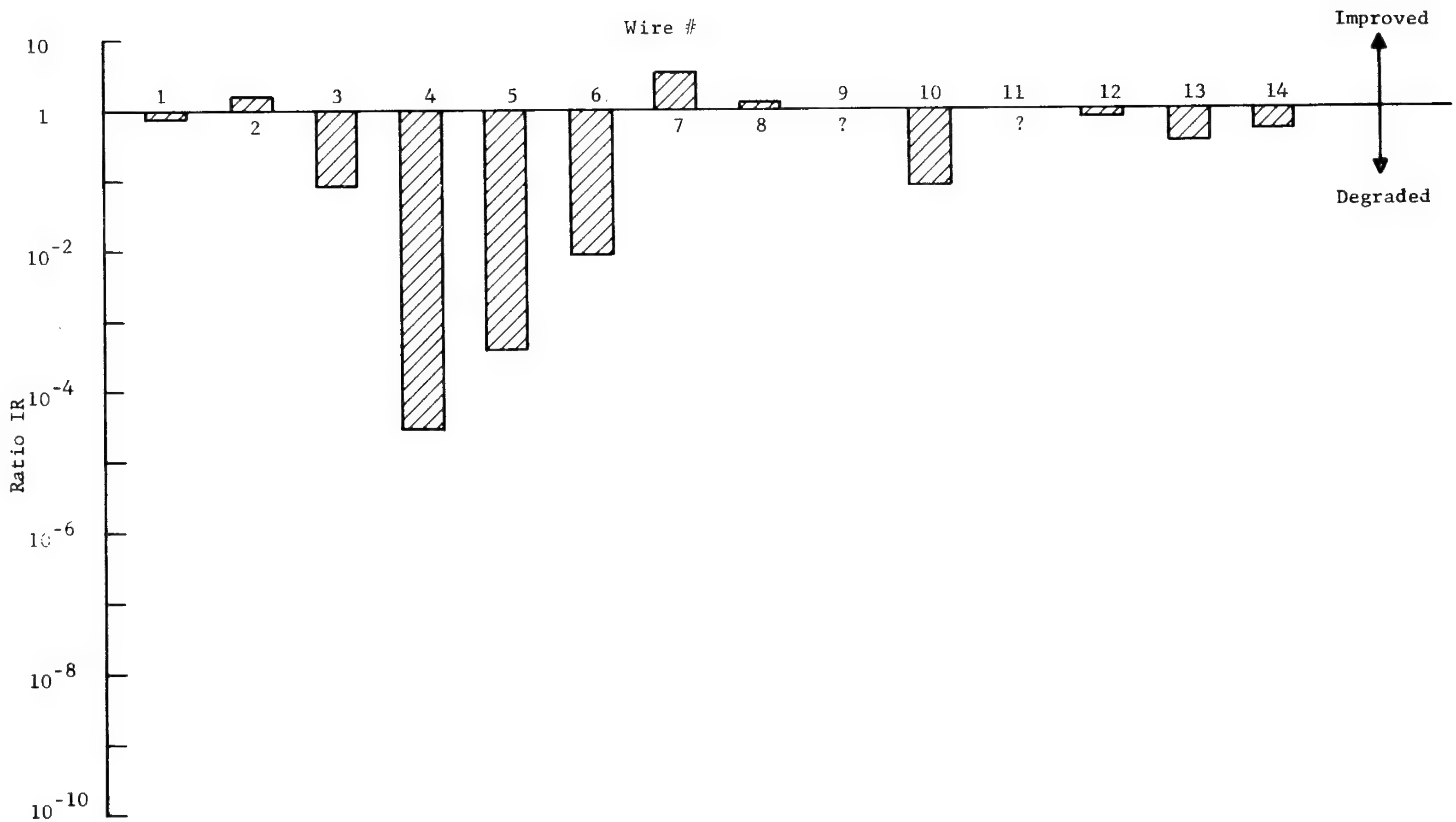

Fig. 26-4 **Ratio of Insulation Resistance - Exposed/Unexposed 14 Days in Salt Fog**

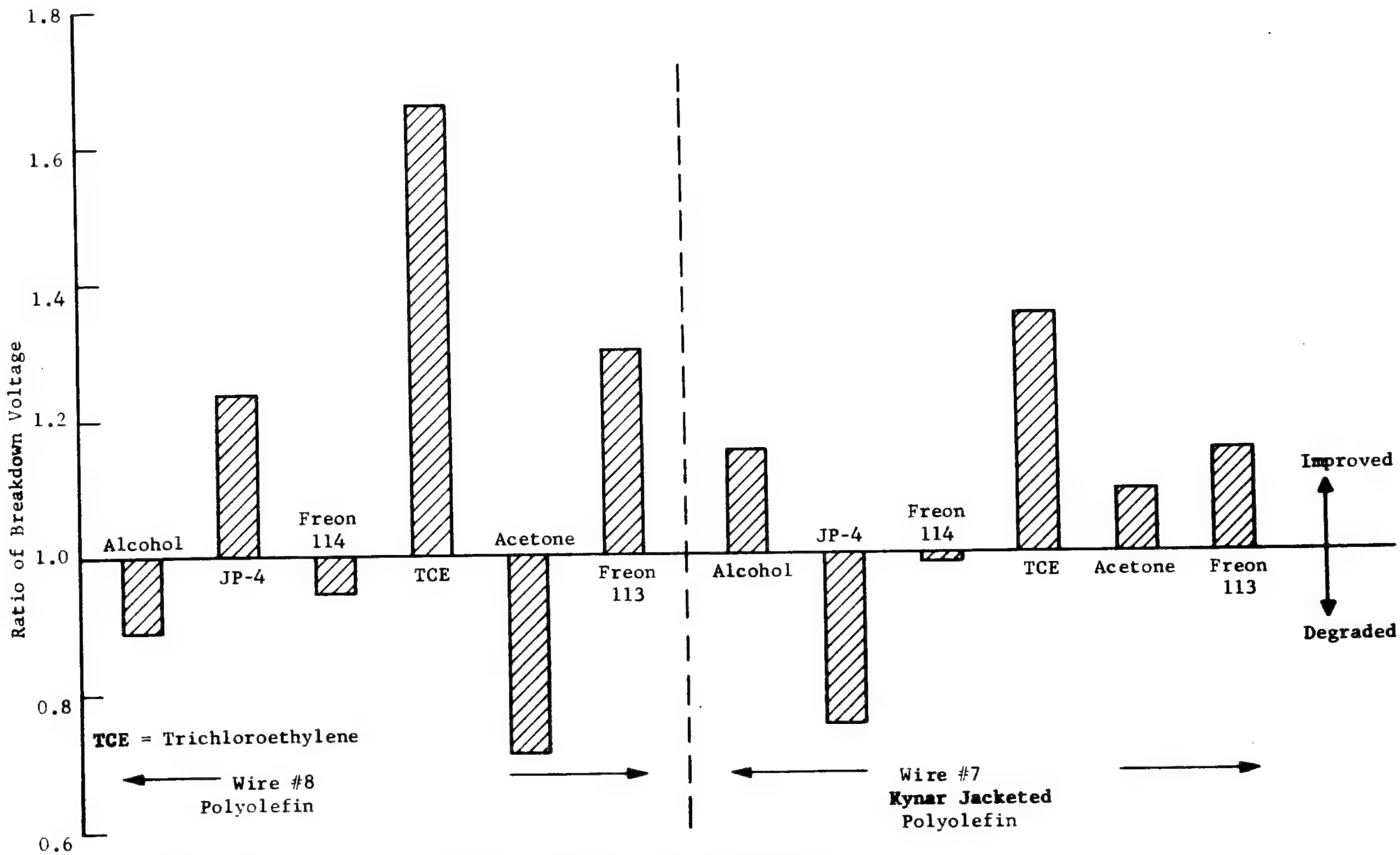

Figure 26-5 - **Ratio of Breakdown Voltage - Exposed/Unexposed**
Comparison of the Effect of 14 Days Exposure to Various Solvents in Wires #7 and #8

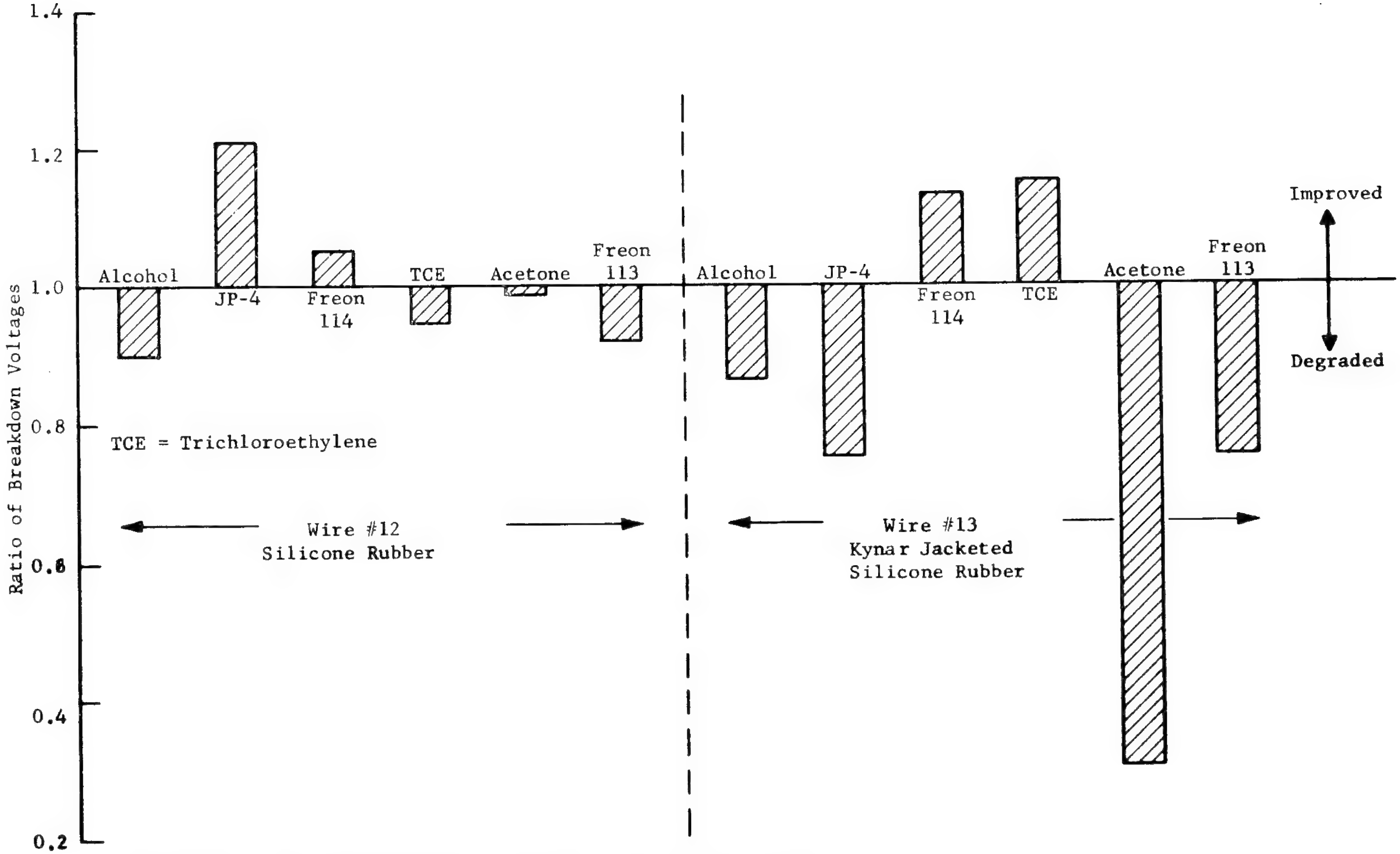

Figure 26-6 - Ratio of Breakdown Voltages - Exposed/Unexposed
Comparison of the Effect of 14 Days Exposure to Various Solvents in Wires #12 and #13

27, 28. Vacuum Volatility and Off-gassing in 5 PSI Oxygen

Except for the polyolefin Wires #7 and 8 and the silicone rubber Wires #12, 13 and 14 the rate of weight loss after 15 hours at 150°C in either vacuum or 5 psi oxygen was too low to measure (less than about .001-.002% per hour based on the weight of the insulation). The estimated rate of weight loss for the polyolefin and silicone rubber insulated wires is given in Table 27, 28-1. It is interesting that the continuing rate of weight loss is higher in the oxygen atmosphere than in vacuum. It is probable that in vacuum most of the volatile materials such as water have been "pulled off" after 15 hours exposure, but in oxygen, a slow degradation continues to create volatile materials. This situation would undoubtedly be even more marked at higher temperatures. The widely held concept that volatility in vacuum is greater than in an atmosphere such as oxygen and air is probably not true at temperatures high enough to cause even a very small amount of insulation degradation. It should be pointed out also that the rate of weight loss in vacuum after 15 hours exposure, shown in Table 27, 28-1, will most likely decrease with increase in time - probably experimentally so that even for the polyolefins and the silicones the rate probably will ultimately decrease to a very low value. On the other hand, in oxygen the rate of weight loss may <u>not</u> decrease nearly so fast with time if at all.

In Figure 27, 28-1 the actual values of weight loss after 15 hours at 150°C have been plotted for exposure to both vacuum and 5 psi oxygen. Unlike the <u>rate</u> of loss, the total value of loss over the first 15 hours is greater in vacuum than in the oxygen atmosphere. This situation might well reverse as time went on. However, it is noteowrthy that only the polyolefin Wires #7 and 8 and the silicone rubber Wires #12, 13 and 14 show a significant weight loss. Several interesting observations can be made:

A. The loss in weight for the Kynar jacketed polyolefin (Wire #7) is greater than for the unjacketed Wire #8. Exactly the reverse is true for Kynar jacketed silicone rubber #13 as compared to Wire #12. It seems possible that irradiation of the polyvinylidene fluoride (Kynar) jacket of Wire #7 produces polymer fragments which are evolved. The Kynar over Wire #13 was not irradiated. It is also possible that a jacket traps absorbed gas

in Wire #7, but that in Wire #13, this effect is overshadowed by the influence of the jacket in reducing volatility from the silicone rubber.

b. The H-film jacket over the silicone rubber (Wire #14) significantly decreases weight loss in both vacuum and the oxygen atmosphere.

c. The weight loss is very low for TFE Teflon (Wire #9) and the unbonded H-film with TFE overwrap (Wire #11). However, even for the other wires (except #7, 8, 12, 13 and 14) the weight loss is so low that it should not constitute a hazard (see Section 29 on analysis).

d. Some of the jacketed or overcoated wires appear to trap absorbed gas. This seems to be true for the loose ML coating on Wire #1 contrasted to the tigher ML coating on Wire #2.

Method of Test

The recording microbalance used in the vacuum volatility program provided more complete and somewhat more sensitive test results than could be achieved with the quartz springs used in the oxygen atmosphere. However, the quart springs are quite inexpensive and did provide adequate comparative results. If time had been available, however, the microbalance would have been used in the oxygen atmosphere also.

TABLE 27, 28-1

AVG. ESTIMATED RATE OF WEIGHT LOSS AT 150°C, BASED ON WEIGHT OF INSULATION % PER HOUR AFTER 15 HOURS EXPOSURE

Wire #	In Vacuum	In Oxygen
7	.034	.063
8	.016	.028
12	.011	.038
13	?	.044
14	.006	.039

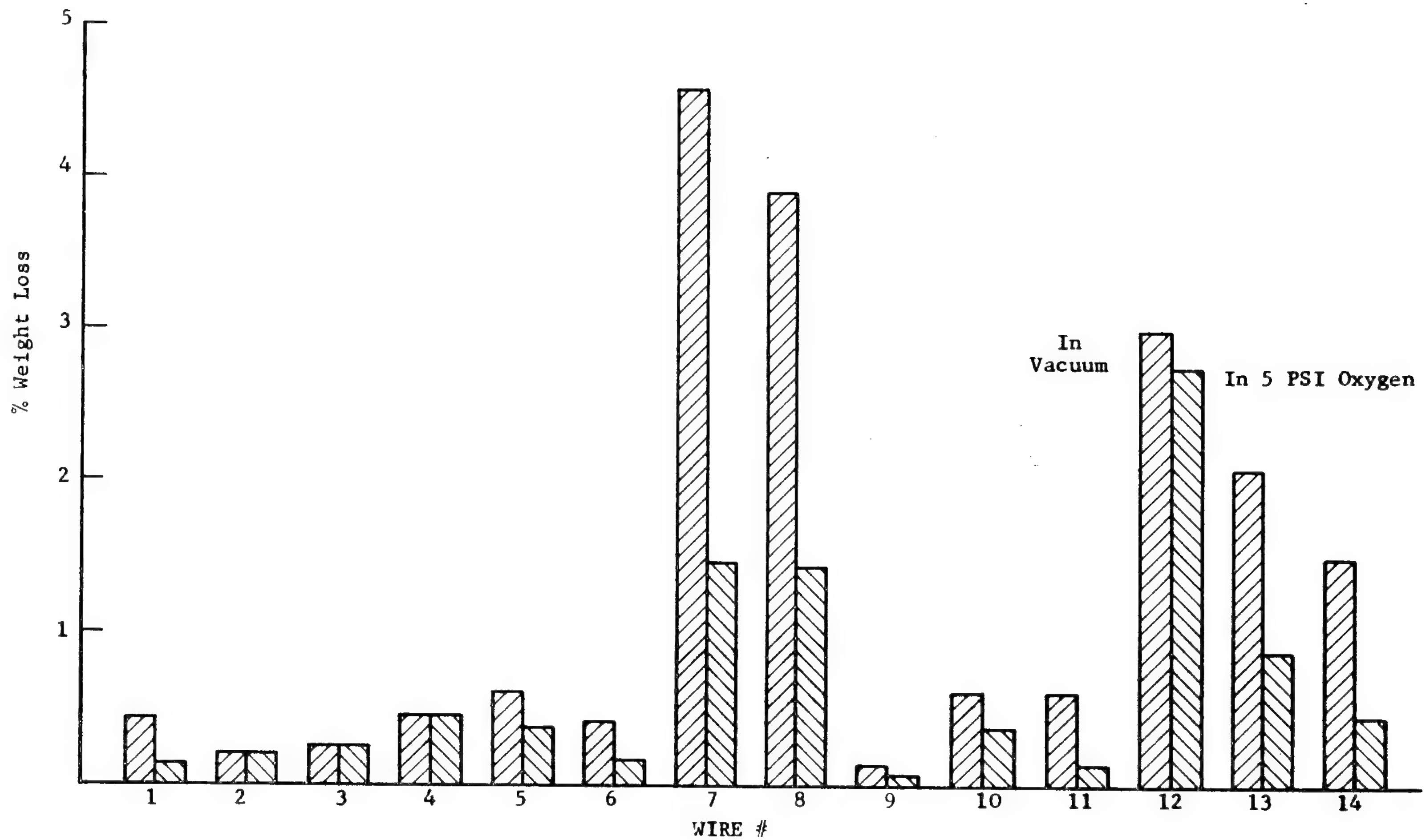

Figure 27,28-1: Percent Weight Loss (Based on Weight of Insulation) After 15 Hours at 150°C in Vacuum or 5 PSI Oxygen

29. Analysis of Evolved Gas

At 150°C in both vacuum and oxygen the major gas evolved is absorbed water with some absorbed nitrogen and carbon dioxide. The very small amount of nitrogen containing gases is believed to come from residual unreacted components in the polyimide polymerization of ML enamel and H-film. The silanes from the silicone rubber are also undoubtedly a low molecular weight fraction in the polymerization.

Toxicology is a complex problem but at 150°C the toxicity of the gases evolved for any of the wires does not seem to be a problem. Of course those wires which evolved the largest amount of gas are the most suspect - the polyolefin and the silicone rubber.

At 300°C chemical decomposition is indicated principally in the polyolefin Wires #7 and 8 and also in the silicone rubber. The appreciable quantities of carbon monoxide for all of the wires does give some concern in respect to toxicity. It must of course be reocgnized that 300°C is not a normal temperature but is rather designed to show what might happen under current overload or other abnormal conditions.

The HF evolved from the Kynar jacket of Wire #7 at 300°C is also sufficiently large to cause concern not only in respect to toxicity but also corrosion. Whey the Kynar jacket of Wire #13 did not also evolve HF is a puzzle. It should be remembered that the Kynar over Wire #7 is irradiated and that over Wire #13 is not. The nitrogen containing compounds evolved from ML enamel and the H-film are also potentially toxic but the amounts evolved are quite small.

Many other comments can be made about the gases evolved at 300°C which are too detailed to be recorded here and reference for them should be made to Volume I.

30. Overall Summary

Even though the foregoing attempts to summarize the very extensive results of this program, it is recognized that overall comparison is still difficult. In consequence, all of the properties for all of the wires are summarized in Table 30-1. It has been necessary to use qualitative rather than quantitative expression in some cases and to omit a considerable amount of subsidiary or complimentary data. In consequence for detailed and thorough analysis, the foregoing sections of this report or Volume I should be consulted.

Even Table 30-1 requires considerable study so the following tabulation provides a brief review and comparison wire by wire - listing advantages and limitations for each.

Wire #1 - ML Overcoated FEP Teflon

Advantages	Limitations
Does not burn.	Poorly adhering ML coating.
Good mandrel flexibility at -196°C.	Failed both qualification tests.
	Tracked on flashover.
	Poor electrical performance in potting compound.
	Poor scrape abrasion resistance.
	Poor cut-through and creep.
	Coating damaged in thermal aging and UV.
	Wicks.
	Salt fog embrittled ML coating.

Wire #2 - ML Overcoated TFE Teflon

Advantages	Limitations
Good scrape abrasion resistance	Failed both qualification tests.
Resistant to thermal aging.	Poor insulation resistance.
Resistant to UV in vacuum.	Poor electrical performance in potting compounds.
Does not burn but glows.	Poor mandrel flexibility at -196°C.
	Poor cut-through and creep.
	Attacked by UV and wet O_2.

Wire #3 - HF Film with TFE Dispersion Coating

Advantages	Limitations
Passed qualification tests.	Tracked on flashover.
Good performance in potting compounds.	Wicks.
Good mandrel flexibility at -196°C.	Attacked by UV and wet O_2.
Good scrape abrasion.	
Excellent cut-through and creep resistance.	
Resistant to thermal aging	
Resistant to hypergolic fuels.	
Does not burn but glows.	

Wire #4 - Thin Wall HF-Film

Advantages	Limitations
Thin wall and light weight.	Failed both qualification tests.
Excellent mandrel flexibility at $-196^{\circ}C$.	Low insulation resistance.
Good cut-through and creep resistance.	Low corona voltage.
Does not burn but smokes.	Difficult to strip.
	Poor scrape abrasion resistance.
	Wicks.
	Attacked by hypergolic fuels.

Wire #5 - Thin Wall HF-Film

Advantages	Limitations
Thin wall and light weight.	Failed both qualification tests.
Excellent mandrel flexibility at $-196^{\circ}C$.	Low insulation resistance.
Fair cut-through and good creep resistance.	Low corona voltage.
Does not burn.	Fair abrasion resistance.
	Wicks.
	Attacked by hypergolic fuels.

LEM Wire #6 - HF-Film with FEP Dispersion Coating

Advantages	Limitations
Passed both qualification tests.	Low corona voltage.
High breakdown voltage.	Tracked on flashover.
Good performance in potting compounds.	Wicks.
Good mandrel flexibility at $-196^{\circ}C$.	Attacked by N_2H_4 and A-50.
Good scrape abrasion resistance.	
Excellent cut-through and creep.	
Does not burn but smokes.	

Wire #7 - IMP with Kynar Jacket

Advantages	Limitations
Passed both qualification tests.	Low corona voltage.
Strip easily.	Tracks with limited flame on flashover.
Good performance in potting compounds.	Poor mandrel flexibility at $-196^{\circ}C$.
No wicking.	Fair abrasion resistance.
	Blocks at $150^{\circ}C$.
	Poor cut-through and poor creep resistance.
	Damaged by thermal aging in O_2.
	Burns with heavy smoke.
	Attacked by hypergolic fuels.
	Considerable outgassing at high rate in both vacuum and O_2.

Wire #8 - Irradiated Modified Polyolefin (IMP)

Advantages	Limitations
Passed both qualification tests	Burned on flashover.
Easily stripped.	Poor mandrel flexibility at -196°C.
Excellent performance in potting compounds.	Fair abrasion resistance.
No wicking.	Blocks at 150°C.
	Very poor cut-through and creep.
	Damaged by thermal aging in 0_2.
	Burns with heavy smoke.
	Attacked by hypergolic fuels.
	Very considerable outgassing at high rate in both vacuum and 0_2.

Wire #9 - Extruded TFE Teflon

Advantages	Limitations
Passed insulation resistance qualification test.	Failed voltage withstand qualification test
High insulation resistance.	Thick wall and heavy.
High corona voltage.	Poor cut-through and creep resistance.
Does not track or flame on flashover.	Wicks.
Easily stripped.	Burns but without visible smoke.
Good performance in potting compounds.	
Fair mandrel flexibility at -196°C.	
Excellent scrape abrasion resistance.	
Resistant to hypergolic fuels.	
Very low off-gassing in vacuum and 0_2.	

Wire #10 - Thin Wall HF-Film

Advantages	Limitations
Light weight.	Failed both qualification tests.
Good mandrel flexibility at -196°C.	Low insulation resistance.
Good cut-through and creep resistance.	Low corona voltage.
Does not burn but smokes.	Poor scrape abrasion resistance.
	Wicks.
	Attacked by hypergolic fuels.
	Poor performance in potting compounds.

Wire #11 - Thin Wall H-Film with TFE Overwrap

Advantages	Limitations
High insulation resistance.	Failed both qualification tests.
Light weight.	Low corona voltage.
Good mandrel flexibility at -196°C	Tracked on flashover.
Does not burn but smokes.	Difficult to strip.
Very low off-gassing.	Poor performance in potting compounds.
	Very poor scrape abrasion resistance.
	Poor cut-through but fair creep resistance.
	Wicked.
	Attacked by N_2H_4 and A-50.

Wires #12 - Silicone Rubber

Advantages	Limitations
High corona voltage.	Failed both qaulification tests.
Easily stripped.	Tracked with limited flame in flashover.
	Very poor mandrel flexibility at -196°C.
	Extremely poor scrape abrasion resistance.
	Extremely poor cut-through and creep resistance.
	Wicked.
	Burns with heavy smoke.
	Attacked by hypergolic fuels, oils and ethylene glycol.
	Considerable off-gassing at high rate in both vacuum and O_2.

Wires #13 and 14 - Jacketed Silicone Rubber

The wall thickness and weight of Wires #13 and 14 rule them out for serious consideration. Moreover, the Kynar jacket over the silicone rubber in Wire #13 generally does not improve the performance. The H-film tape overlap improves only a few properties such as cut-through resistance.

Wire #15 - HF-Film
(Limited Data)

Advantages	Limitations
Light weight.	Failed both acceptance tests.
Good mandrel flexibility at -196°C.	Tracked on flashover.
Fair scrape abrasion resistance.	Wicked.
Good cut-through and creep resistance.	Burns with smoke.

Wire #16 - HF-Film with TFE Dispersion Coating
(Limited Data)

Passed both acceptance tests.	Tracked on flashover.
Excellent mandrel flexibility at -196°C.	Wicked.
Good scrape abrasion resistance.	Burns with smoke.
Excellent cut-through and creep resistance.	

No recommendations are made for final selection of specific wires for specific applications because, as stated in the beginning, each wire has advantages and disadvantages. However, some generalizations can be made.

1. The silicone rubber insulated wires evaluated in the program do not seem to be suitable for most spacecraft applications.

2. The polyolefin insulated wires both with and without a Kynar jacket have limited usefulness at least in an oxygen atmosphere for most spacecraft applications.

3. The ML overcoated Teflon insulated wires are not sufficiently better than Teflon alone to justify their use. However they may be made with somewhat (but not much) thinner walls. The lighter weight may be desirable.

4. The flexibility and cut-through as well as creep resistance of H-film tape constructions is outstanding if properly made (not too thin). Overall performance is improved by adequate Teflon coatings.

Finally, it is concluded that an improved specification is needed for hook up wire to be used in spacecraft applications. Special attention needs to be directed particularly to problems associated with thin wall constructions and oxygen atmospheres.

TABLE 30-1: OVERALL SUMMARY OF TEST RESULTS

	#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	#12	#13	#14	#15	#16
Insulation Resistance Total Sample-3 Days in H_2O Voltage Withstand - 1600 volts	Failed	Failed	Passed	Failed	Failed	Passed	Passed	Passed	Passed	Failed	Failed	Failed	Failed	Failed	Failed	Passed
Total Sample - 3 Days in H_2O	Failed	Failed	Passed	Failed	Failed	Passed	Passed	Passed	Failed	Failed	Failed	Failed	Failed	Failed	Failed	Passed
Insul. Resist-15 Days in Wet O_2, 50°C - Range, ohms	0.36-2.5 $x10^{13}$	$2.5x10^{5}$ $2.0x10^{14}$	0.74-1.1 $x10^{13}$	1.0-8.0 $x10^{10}$	3.3-4.5 $x10^{10}$	0.71-1.1 $x10^{12}$	1.0-2.9 $x10^{13}$	1.3-1.5 $x10^{13}$	1.9-5.0 $x10^{14}$	4.7-5.7 $x10^{11}$	0.33-8.3 $x10^{14}$	2.0-3.1 $x10^{12}$	1.0-1.7 $x10^{12}$	1.6-3.1 $x10^{12}$	-- --	-- --
Corona-5 psi dry O_2, Min. KV Start	0.84	0.80	0.80	0.62	0.60	0.60	0.76	1.0	1.1	0.56	0.67	0.95	0.81	1.0	--	--
Extinct	0.75	0.75	0.75	0.57	0.57	0.73	0.65	0.96	0.92	0.51	0.64	0.88	0.88	0.95	--	--
Volt. Bd. Min. KV Fast rate of rise — Normal Air -23°C	15.8	15.0	25.5	17.5	13.0	25.5	21.0	26.0	14.5	18.0	19.5	16.5	18.0	20.6	20.0	24.0
Vacuum 150°C	11.0	14.0	11.8	6.5	8.5	11.5	11.0	11.5	13.5	8.5	10.0	10.5	12.0	10.5	10.0	--
5 psi wet O_2-23°C	12.0	13.0	16.5	10.5	13.0	21.0	12.5	16.5	15.6	8.5	8.0	14.5	17.0	16.5	21.5	21.0
Flashover-5psi wet O_2-23°C	Tracked	No Track	Tracked	Tracked Slowly	Tracked Slowly	Tracked	Tracked Limited Flame	Burned	No Track	Tracked Slowly	Tracked	Tracked Limited Flame	Burned	Tracked	Tracked	Tracked
Nominal Wall Thickness - mils	6.7	6.7	7.1	2.9	3.4	6.7	7.4	9.7	10.6	8.5	8.2(?)	7.3(?)	12.5	10.0	--	--
Concentricity - %	84.7	86.3	84.7	<80	>80	85.7	90.3	91.7	89.6	80	<80	>80	>80	>80	--	--
Weight per 1000 ft. - lbs. avg.	4.50	4.86	4.80	4.22	4.36	4.45	4.65	4.65	5.43	4.21	4.21	4.95	5.36	5.41	4.33	4.46
Stripability - Mechanical	Easy	Easy	Easy	NG	Easy	Easy	Easy	Easy	Easy	Easy	NG	Easy	Easy	Easy	Easy	Easy
Thermal	Easy	Easy	Slow	Slow	Slow	Easy	Easy	Easy	Easy	Slow	Slow	Easy	Easy	Easy	Slow	Slow
Color changed by (Fuels and oxidizers excluded)			Slight UV in Vac				150°C-in O_2,Vac,UV	150°C-in O_2,Vac,UV Hyd. Oil								
Marking - Affected by - Condition Fuels and Oxidizers	No Test	$UV-O_2$ Yes except N_2O & UDMH	No except N_2O_4	No Test	No Test	No	No	$UV-O_2$ No except Fluorine		$UV-O_2$ Yes except UDMH & F_2		No except Fluorine	No Test	No except A-50	-- -- --	-- -- --
Min. Pull-Out Strength-lbs. Potting Compounds — RTV Sil #1933	11.2	8.8	20.4	15.3	15.5	18.6	18.3	19.2	12.0	6.7	4.0	14.3	16.9	9.5	--	--
Silicone #1663	9.9	8.5	12.6	12.7	11.7	12.3	9.5	2.6	7.7	8.8	3.5	11.7	4.7	10.4	--	--
Epoxy XR5038	14.2	10.1	33.8	28.6	14.9	26.5	24.7	22.9	9.6	10.7	3.2	11.2	0.4	7.4	--	--
Polyurethane #794	9.4	3.1	6.0	10.2	7.0	4.9	10.2	12.4	11.0	5.4	3.9	1.4	7.6	4.6	--	--
Min. Volt. Bd. Potting Compounds — RTV Sil #1933	<0.5	3.1	<0.5	3.0	<0.5	12.5	13.0	7.5	9.5	<0.5	<0.5	11.1	8.3	11.1	--	--
Silicone #1663	0.4	11.6	20.0	9.0	6.0	12.5	7.0	9.0	17.6	0.5	0.2	8.5	4.9	7.1	--	--
Epoxy XR5038	<0.5	12.6	10.0	9.0	4.5	15.8	15.7	15.5	8.0	7.5	3.0	4.2	3.1	10.3	--	--
Polyurethane #794	0.5	1.5	3.5	1.6	<1.0	4.0	3.9	11.6	1.5	short	short	1.0	6.0	4.0	--	--
Mandrel Flexibility - Fail Dia. In -196°C	0.75	1.75	0.25	.075	.075	0.25	1.75	>3.0	0.5	0.25	0.25	>3.0	3.0	3.0	0.5	0.125
Repeated Flex at 23C - Avg.	2570	2680	5037	1866	2240	6081	4332	4053	1818	2515	1793	1883	3323	1513	6551	6935
- 162°C Failure	506	245	3727	3133	3457	2633	1771	815	8252	9615	3181	355	577	259	3783	2159
Scrape - Strokes 500 grams	508	19,947	28,119	215	1255	10,347	1545	6391	150,000 Est.	386	33	2.6	NT	NT	8837	11,747
Abrasion - Strokes 1000 grams	6	29	239	14	68	285	787	188	941	23	4	N.T.	39	116	114	167
Blocking	None	None	None	None	None	None	Pressure at 150°C	Pressure at 150°C	None	None	None	None	None	None	None	None
Cut-through-lbs. Failure — 23°C	36	31	111	84	56	119	20	16	25	117	43	3	20	85	84	117
149°C	15	19	53	33	34	54	3	0.5	8	78	34	2	5	36	66	55
Creep - lbs. range Est. 1 hr. failure — 23°C	105-110	100-110	300-325	160-170	210-275	410-425	<96	<116	116	275-300	175-180	<116	<116	<116	185-200	350-370
149°C	<25	40-45	110-130	85-100	90-100	225-240	<33	<23	33	225-240	70-90	<33	<33	<33	125-140	170-180
Wicking - inches	3 to 5	2 to 3	6	6	3 to 5	3 to 5	1/8 to ¼	1/8 to ¼	2 to 3	6	2 to 3	2 to 3	2 to 3	2 to 3	6	6

TABLE 30-1: OVERALL SUMMARY OF TEST RESULTS (Continued)

		#1	#2	#3	#4	#5	#6	#7	#8	#9	#10	#11	#12	#13	#14	#15	#16
Thermal Aging Damage 15 Days-150°C	Vacuum	Yes	No	No	No	No	No	No	No	No	No	No	No	No	No	--	--
	O_2	Yes	No	No	No	No	No	Yes	Yes	No	No	No	No	No	No	--	--
30 Days UV Damage	30 Days-150°C Vac.	Yes	No	No	No	No	No	No	No	No	No	No	No	No	No	--	--
	30 Days, 95°C-wet O_2	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	No	Yes	Yes	No	--	--
Flammability (SE - Self Extinguished) in 5 PSI wet O_2		Flame-SE	Glow	Glow	No	No	No	Burns	Burns	Burns	Flame-SE	No	Burns	Burns	Burns	Burns	Burns
	Smoke	Yes	Yes	Yes	No	Yes	Yes	Heavy	Heavy	No	Yes	Yes	Heavy	Heavy	Heavy	Yes	Yes
Chemical Compatibility Degraded by	Fuels	None	None	None	All	All	N_2H_4 & A-50	All	All	None	All	N_2H_4 & A-50	All	All	All	--	--
	Oxidizers	N_2O_4	N_2O_4	N_2O_4	N_2O_4 & F	N_2O_4 & F	N_2O_4 & F	N_2O_4	N_2O_4	N_2O_4	N_2O_4	N_2O_4	N_2O_4 & F	N_2O_4 & F	N_2O_4 & F	--	--
	Others	Salt Fog	Salt Fog		Salt Fog	Salt Fog	Salt Fog		Salt Fog	None		Salt Fog	Oils Ethyl Glycol	Oils Acetone	Oils		
Off-Gas in O_2 %/gm. Insul.	15 hrs. at 150°C	0.15	0.23	0.27	0.45	.09	0.19	1.43	1.40	.085	0.37	.06	1.75	0.85	0.46	--	--
	rate / hr.	low	low	low	low	low	low	.063	.028	low	low	low	.039	.044	.039	--	--
Volatility in Vac. %/gm. Insul.	15 hrs. at 150°C	0.44	0.22	0.27	0.24	0.60-	0.45	4.52	3.92	.013	.057	.058	2.99	2.06	1.50	--	--
	rate / hr.	<.0021	<.0015	<.0015	<.0016	<.0013	<.0018	0.29	0.16	<.001	<.002	<.003	?	?	.006	--	--
Mol % at 150°C																	
Gas Analysis H_2O	In Vac.	58	78.2	94.7	94.2	97.9	96.1	79.3	98.2	71.3	97.0	85	89.1	95	96.6	--	--
	In O_2	65	7	99.3	98.6	47	98.6	75.0	83.6	77.0	98.8	100	95.8	9	21.6	--	--
N_2 less H_2O in Vac.		--	0.9	72	69	66.5	67	Trace	11	54	54.5	49	46	34	30	--	--
CO_2 less N_2 and H_2O	In Vac.	36	44	65	38	96	100	68.5	74.5	70	66	78.5	85	33	20	--	--
	In O_2	69	87	73	100	100	94	?	55	100	100	--	88	100	60	--	--
Mol % at 300°C																	
H_2O	In Vac.	27	67.7	40.6	63.1	44.2	66	45.7	17.8	38.5	71.9	32.6	50.4	53.6	60.6	--	--
	In O_2	10.5	45.0	25.2	28.7	1.4(?)	27.3	10.7	10	25.2	48.9	23.0	36	36.5	20	--	--
CO_2	In Vac.	45.6	20.6	24.6	24.7	22.8	23	19.8	63.0	23.4	16.1	31.5	8.8	18.0	16.2	--	--
	In O_2	84	51.7	60.6	69.7	97.3(?)	72.7	41.8	54	71.6	50.0	13.6	52	60	69	--	--
CO	In Vac.	17.0	3.8	5.7	7.9	3.6	1.5	7.9	4.6	32	4.3	16.6	2.9	3.9	1.6	--	--
	In O_2	5.5	?	?	?	?	?	45.2	30	?	?	?	8	10	8.5	--	--

? - Data questionable or amount too small to measure.